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GEORGE C. LLOYD
SECRETARY



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1929

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PREFACE.

THE present volume of the *Journal of the Iron and Steel Institute* contains the Presidential Address of Professor Henry Louis; the "Third Report on the Heterogeneity of Steel Ingots," prepared by a Committee of the Institute, under the Chairmanship of Dr. W. H. Hatfield; the "First Report on Blast-Furnace Plant and Practice," prepared by Committee No. 2 of the Institute, under the Chairmanship of Mr. A. K. Reese; and thirteen other papers—all presented at the Annual Meeting held in London, together with the discussion and correspondence thereon. It also contains a report of proceedings and speeches at the Annual Dinner held at the Connaught Rooms on May 2.

Section II. contains the usual notes on the progress of the home and foreign iron and steel industries as reported in the proceedings of scientific and technical societies and in the technical press, together with notices of new books presented to the Institute, and a bibliography of the principal works dealing with the metallurgy of iron and steel and allied subjects which have appeared during the last half-year.

In front of the title-page is inserted a list of the British Standardised Steel Samples issued jointly by the Iron and Steel Institute and the National Physical Laboratory, showing where and on what terms the samples are available.



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ABBREVIATIONS USED IN TEXT.

Å.	Ångström unit(s).	hr.	hour(s).
a.c.	alternating current(s).	in.	inch; inches.
amp.	ampère(s).	in.-lb.	inch-pound(s).
amp.-hr.	ampère-hour(s).	K.	absolute temperature (scale).
atm.	atmosphere(s) (pressure).	kg.	kilogramme(s).
Bé.	Baumé (scale).	kg.-m.	kilogramme-metre(s).
B.H.P.	brake horse-power.	km.	kilometre(s).
B.O.T.	Board of Trade.	kva.	kilovolt-ampère(s).
B.th.u.	British thermal unit(s).	kw.	kilowatt(s).
B.T.U.	Board of Trade unit(s).	kw.-hr.	kilowatt-hour(s).
B.W.G.	Birmingham wire-gauge.	lb.	pound(s).
C.	centigrade (scale).	L.-F.	low-frequency.
cal.	calory; calories.	m.	metre(s).
c.c.	cubic centimetre(s).	m.-amp.	milliampère(s).
c.d.	current density.	m.-volt	millivolt(s).
cg.	centigramme(s).	max.	maximum.
c.g.s.	centimetre - gramme - second unit(s).	mg.	milligramme(s).
cm.	centimetre(s).	min.	minimum; minute(s).
coeff.	coefficient.	mm.	millimetre(s).
const.	constant(s).	m.m.f.	magnetomotive force(s).
c.p.	candle-power.	N.	normal (solution).
cu.	cubic.	N.T.P.	normal temperature and pressure.
cwt.	hundredweight(s).	O.-H.	open-hearth; oil-hardened.
d.c.	direct current(s).	oz.	ounce(s).
dg.	decigramme(s).	p.d.	potential difference.
diam.	diameter(s).	R.	Réaumur (scale).
dm.	decimetre(s).	r.p.m.	revolutions per minute.
e.m.f.	electromotive force(s).	sec.	second(s).
F.	Fahrenheit (scale).	sp. gr.	specific gravity.
ft.	foot; feet.	sq.	square.
ft.-lb.	foot-pound(s).	T.	tempered.
gal.	gallon(s).	temp.	temperature.
grm.	gramme(s).	v.	volt(s).
H.-F.	high-frequency.	va.	volt-ampère(s).
H-ion	hydrogen-ion.	w.-hr.	watt-hour(s).
H.P.	horse-power.	yd.	yard(s).
H.P.-hr.	horse-power-hour(s).	°	degree(s).

SECTION I.

*MINUTES OF PROCEEDINGS
AND PAPERS OF
THE IRON AND STEEL INSTITUTE.*

ANNUAL MEETING

1929.

Editorial assistance has been given by A. E. CHATTIN, B.Sc. (Hons. Met.),
Assistant Secretary, in the preparation of this Section.

MINUTES OF PROCEEDINGS

AND

PAPERS AND DISCUSSIONS

AT THE

ANNUAL MEETING, 1929.

THE SIXTIETH ANNUAL GENERAL MEETING OF THE IRON AND STEEL INSTITUTE was held at the Institution of Civil Engineers, Great George Street, Westminster, on Thursday and Friday, May 2 and 3, 1929. Mr. BENJAMIN TALBOT, the retiring President, took the Chair, and was succeeded by Professor HENRY LOUIS, M.A., D.Sc.

The Minutes of the last General Meeting were taken as read and confirmed.

SCRUTINEERS.

Dr. A. BRAMLEY (Loughborough) and Mr. A. ALLISON (Sheffield) were appointed scrutineers of the ballot for the examination of the voting papers, and they subsequently announced that the following sixty-three candidates for membership and seven candidates for associateship had been duly elected :

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PRESENTATION OF ANNUAL REPORT AND STATEMENT OF ACCOUNTS FOR 1928.

The PRESIDENT said the Annual Report of Council had been circulated, and, with the permission of the members, he proposed that it be taken as read. He then asked the Honorary Treasurer to submit his report on the Accounts.

Professor H. C. H. CARPENTER, F.R.S. (Hon. Treasurer), in presenting the Balance Sheet and Statement of Accounts of the Institute for 1928, said that it had been his invidious task for three years in succession to have to record a deficit. It was, therefore, all the more satisfactory to him to be able to report, for the first time in four years, that they were able to carry forward a surplus, though not a very large one ; it amounted actually to £22. When the position was compared with that of 1927, for which year the accounts had shown a deficit of £879, he thought the Council were to be congratulated on what appeared to be

a good step towards putting the finances of the Institute on a sounder footing. The total income in 1928 had been £7940, or about £109 more than in 1927. The expenditure had been £7918, which was nearly £800 lower than the year before. It had been pointed out a year ago that the item mainly responsible for the large and increasing expenditure was the amount spent on publications. In the year under review, the Council had succeeded, by rigid economy, in reducing the outlay under that head by about £500, and it was chiefly by that cut that they had been able to balance the accounts. Still, it could not be said that the financial position of the Institute was a satisfactory one so long as the income was so small as to oblige the Council to restrict the work of the Institute in its most useful sphere—namely, the publication of technical and scientific papers and expenditure on research work under the direction of the various technical committees. The item, Annual Subscriptions, which formed the chief source of income of the Institute, unfortunately still showed a decrease, though a much smaller one than in the last four years. In that respect, however, he thought it could be stated with confidence that they had touched the lowest point, as there had been a substantial increase in the receipts from entrance fees (£280, compared with £153 in 1927). That was a welcome indication that new members were coming forward for election in increasing numbers, the effect of which, it was hoped, would be reflected in the next year's accounts. At all events, they were able to record, for the first time in the last few years, a net increase in the membership amounting to 25, bringing the total number of members on the register up to 2008. It was hoped, by increasing the activities of the Institute in the direction of holding meetings in local centres and by other means, to stimulate interest in the work of the Institute and to attract even more new members from those districts.

He had much pleasure in moving the adoption of the Statement of Accounts.

The resolution was unanimously adopted.

REPORT OF COUNCIL.

THE Council of the Iron and Steel Institute have much pleasure in submitting for the approval of the members at this, the Sixtieth Annual General Meeting, their Report on the proceedings and work of the Institute during the year 1928.

ROLL OF THE INSTITUTE.

During the past year one hundred and thirty-eight new members and five associates were elected; eight associates were transferred to membership, and five members were reinstated. Sixty-three members resigned their membership during the year, and the names of twenty-five members were removed from the register owing to the non-payment of their subscriptions. The total membership of the Institute on the register on December 31, 1928, was accordingly as follows:

Patron	1
Honorary Members	5
Life Members	77
Ordinary Members	1911
Associates	14
<hr/>	
Total	2008

It is satisfactory to record that there is an increase of twenty-five in the total membership as compared with 1927.

The Council deeply regret to have had to record the deaths of the following twenty-one members of the Institute which occurred during the year 1928:

Boyes, B. W. (Stockton-on-Tees)	June 18.
Brock, J. P. (Lebanon, U.S.A.)	April 9.
Bumby, H. (Nantwich)	May.
Caspersson, O. F. (Stockholm)	June 28.
Charlton, W. (Guisborough, Yorks)	March 13.
Clamens, J. B. (Paris) (Life Member) . . . . .	...
Dyrssen, Dr. Waldemar (Pittsburgh, U.S.A.)	August.
Eccles, H. (Briton Ferry)	August 12.
Horngren, Consul C. G. (Stockholm) . . . . .	...
Howell, S. E. (Sheffield)	April 15.
Kennedy, Myles (Ulverston)	August 9.

Koboyashi, S. (Muroan, Japan) . . . . .	...
Lamberton, Andrew (Coatbridge) (Hon. Vice-President)	August 23.
Lewis, Colonel David (Glamorgan)	May 30.
Mayrisch, E. (Luxemburg)	March 5.
Mountain, W. C. (Newcastle-on-Tyne)	January 26.
Raine, J. E. (Newcastle-on-Tyne)	September 4.
Schrödter, D.Ing.h.c. Emil (Mehlem-Rhein, Germany) (Hon. Member)	October 31.
Sheldon, F. (Sheffield)	May 3.
Timmermans, F. (Liège)	September 23.
Williams, Daniel (Llanelly)	May.

The deaths of the following four members took place prior to 1928, but were not reported to the Council until that year :

Bartlett, J. H. (Kentucky, U.S.A.)	December 17, 1927.
Forsdike, A. J. (Sheffield)	December 25, 1927.
Howat, W. (Glasgow)	July 30, 1927.
Milne, I. B. (Matlock)	May 18, 1926.

The Council specially wish to place on record their sense of the great loss to the Institute incurred through the deaths of the following : Mr. Andrew Lamberton, who had served on the Council since 1905, and was elected a Vice-President in 1914. He was also a Bessemer Medallist of the Institute ; Mr. E. Mayrisch, President of the Aciéries Réunies Burbach-Eich-Dudelange at Luxemburg. It will be remembered that Mr. Mayrisch received and entertained a party of members on the occasion of their visit to Luxemburg in 1921 ; Dr. E. Schrödter, the well-known General Secretary (retired) of the German Society of Ironmasters, who on two occasions acted as Hon. Secretary of Autumn Meetings of the Institute in Germany ; and Mr. F. Timmermans, who was a member of the Reception Committee which entertained the members on the occasion of the Brussels Meeting in 1913. Obituary notices of these and of other members deceased will be found in the last volume of the Journal.

ELECTION OF HON. MEMBER AND HON. VICE-PRESIDENT.

In the past year the Conde de Zubiría of Bilbao has been elected an Honorary Member. He was originally elected a member of the Institute in 1883.

The Council have also elected Mr. Alfonso de Churruca of Bilbao an Honorary Vice-President of the Institute.

HONOURS CONFERRED ON MEMBERS.

The Council tender their most hearty congratulations to several members of the Institute upon whom appointments of honour and distinction have been recently conferred.

Sir John Dewrance, K.B.E., M.Inst.C.E., M.I.Mech.E., has been created a G.B.E. Mr. M. Mannaberg has been appointed Consul-General for Austria. His Majesty the King of Sweden has been pleased to confer upon Sir W. Peter Rylands, J.P., the Order of Commander of the Royal Order of Vasa, and on Mr. G. C. Lloyd (Secretary) the Order of a Knight of the North Star. Mr. Eugene Schneider has been created an Officer of the Legion of Honour. Mr. G. Hoyland has been appointed a Justice of the Peace for the West Riding of Yorkshire.

Mr. Benjamin Talbot, President of the Institute for 1928, has been elected an Honorary Member of the American Iron and Steel Institute.

Sir Hugh Bell, Bt., C.B., has been elected for the twenty-seventh successive year to be Chairman of the Tees Conservancy Commission. Sir Robert Hadfield, Bt., F.R.S., has been elected a Foreign Associate of the National Academy of Sciences, Washington. Mr. Léon Greiner has been elected President of the Association des Ingénieurs sortis de l'Université de Liège, and Mr. Colin Gresty has been selected for the Presidency of the Newcastle and District Branch of the Institute of British Foundrymen. Sir Robert Hadfield, Bt., F.R.S., Professor H. C. H. Carpenter, F.R.S., and Professor C. H. Desch, F.R.S., have been invited to join the Advisory Committee on Metallurgical and Engineering Research on Materials of the National Physical Laboratory. Mr. P. B. Henshaw has been elected President of the Sheffield Metallurgical Association for 1929.

Sir Robert Hadfield has been awarded the Silver Medal of the Institution of Marine Engineers. Professor H. C. H. Carpenter, F.R.S., has received the Thomas Turner Gold Medal awarded by the Thomas Turner Prize Trust in recognition of special attainments in metallurgy. Dr. J. A. Mathews was the recipient of the Hunt Gold Medal. Mr. P. D. Merica, Ph.D., was presented with the James Douglas Medal for 1928 by the American Institute of Mining and Metallurgical Engineers. Dr. J. W. Donaldson was awarded the Oliver Stubbs Gold Medal by the Council of the Institution of British Foundrymen. Mr. J. G. Pearce was awarded the first prize of 100 guineas by the Glasgow and West of Scotland Association of Foremen, Engineers, and Draughtsmen, for a series of practical

proposals relating to "Goodwill in Industry." Dr. D. H. Ingall has been appointed Principal of the Constantine Technical College, Middlesbrough. Mr. E. W. Fell has been awarded the title "Doktor-Ingenieur" by the Technische Hochschule, Aachen; he is the first Englishman to gain this distinction since the war.

FINANCE.

The Statement of Accounts for the year 1928, which has been duly audited and certified by Messrs. W. B. Keen & Co., the Institute auditors, accompanies this Report, and is presented by Professor H. C. H. Carpenter, F.R.S., the Honorary Treasurer, for the approval of the meeting.

The income for the year under review, apart from that of the Carnegie Scholarship Fund and of the Special Purposes Fund, was £7940, and the expenditure was £7918. The comparative figures of the income and expenditure for the last five years are shown herewith:

					Income.	Expenditure.
					£	£
1923	.	.	.	.	8095	8012
1924	.	.	.	.	8068	7568
1925	.	.	.	.	7952	8084
1926	.	.	.	.	8136	8160
1927	.	.	.	.	7831	8710

The accounts for 1928 show a considerable improvement as compared with those of 1927, when there was an adverse balance of £879. For the first time in the last four years it is possible to carry forward a surplus, though a very modest one, of £22.

MEETINGS.

The Annual Meeting of the Institute was held in the Hall of the Institution of Civil Engineers, by kind permission of the Council of that body, on Thursday and Friday, May 3 and 4, 1928, the Chair being taken by the President, Mr. Benjamin Talbot.

The Annual Dinner was held at the Connaught Rooms on the evening of Thursday, May 3, and was attended by some 300 members and guests. Speeches were delivered by Mr. F. W. Harbord, C.B.E. (Past-President); the Marqués de Merry del Val (Spanish Ambassador); Mr. Alfonso de Churruca; Mr. Charles M. Schwab (President of the American Iron and Steel Institute); the Right Hon. John Hodge; and the President.

The Autumn Meeting of the Institute was held, by the kind invitation of the members of the Institute resident in the Bilbao district, in Bilbao, on September 25 to 27, 1928, and was attended by about 110 members and their ladies. Leaving London on the 21st, the outward journey was broken at San Sebastian, where the party was lavishly entertained by the President of the Province of Guipuzcoa, the Municipal Authorities of the City, and the metallurgical works in the district. The party then proceeded to Bilbao, where they were again entertained in a most hospitable manner by the President of the Province of Vizcaya, the Municipal Authorities of Bilbao, and the metallurgical works and mines in and about the City. Meetings for the presentation and discussion of papers were held on September 25 to 27, and visits to works, mines, and places of interest in the locality were also made.

Following the meeting, a large proportion of the party travelled on to Burgos, Madrid, Sagunto, Cordoba, and Seville. From Madrid whole-day excursions were also made to Toledo and to the Royal Palace of the Escorial.

The success of the meeting was very largely due to the careful forethought and arrangements of the Local Reception Committee, and the results of their labour were very much appreciated. A full account of the meeting and the visits and excursions in connection therewith is published in the last volume of the Journal.

Adjourned local meetings were held in two centres following the two General Meetings in the year. Following the May Meeting, an adjourned meeting was held in the Mappin Hall of the University of Sheffield on May 10, 1928, at which over 90 members and their friends were present; Mr. Frank W. Harbord, C.B.E., was in the Chair. Following the Autumn Meeting, an adjourned meeting was held at the Engineers' Club, Birmingham, on October 25, 1928, under the Chairmanship of Mr. George Hatton, C.B.E.; about 50 members and their friends took part in the proceedings.

Both adjourned meetings were very successful, and thanks are particularly due to the local organisers for their trouble and careful forethought in making the arrangements.

BESSEMER MEDAL.

For the year 1928 the Bessemer Gold Medal was awarded by the Council to Mr. Charles M. Schwab in recognition of his eminent services in promoting the progress of the iron and steel industries.

PAPERS.

Twenty-five papers were contributed to the Proceedings of the Institute during the year. Of these, seventeen papers were presented at the Annual Meeting and eight at the Bilbao Meeting. The following is a complete list :

SECOND REPORT ON HETEROGENEITY OF STEEL INGOTS. By a Committee of the Institute.

BALZOLA, J.—“Iron Ore Mining in Vizcaya.”

CROOKE, A., and T. THOMSON—“The New Plant of the Appleby Iron Co., Ltd.”

EDWARDS, C. A., and T. YOKOYAMA—“The Influence of Varying Strains and Annealing Temperatures on the Growth of Ferrite Crystals in Mild Steel.”

EVANS, E. C., and F. J. BAILEY—“Blast-Furnace Data and their Correlation.”

EVEREST, A. B., and D. HANSON—“The Influence of Nickel in Iron-Carbon-Silicon Alloys containing Phosphorus.”

FRIEND, J. NEWTON—“A Study of the Resistance of Over-Stressed Wrought Irons and Carbon Steels to Salt-Water Corrosion.”

HARBORD, V.—“A Comparison of the Most Important Methods Employed in the Cleaning of Blast-Furnace Gas.”

HATFIELD, W. H.—“Heat-Resisting Steels. Part II.—Mechanical Properties.”

HERRERO, A., and M. DE ZUBIRIA—“The Phenomena of Corrosion of Iron and Steel.”

HOLGATE, J. E., and R. R. F. WALTON—“Blast-Furnace Practice in Natal.”

JONES, J. A.—“The Properties of Nickel Steels, with Special Reference to the Influence of Manganese.”

JONES, J. H., J. G. KING, and F. S. SINNATT—“Reactivity of Coke.”

NORBURY, A. L., and T. SAMUEL—“The Recovery and Sinking-In or Piling-Up of the Material in the Brinell Test, and the Effects of these Factors on the Correlation of the Brinell with certain other Hardness Tests.”

O'NEILL, H.—“Twin-Like Crystals in Annealed α -Iron.”

ORLAND, J.—“The Influence of Pearlitisation below the A_{r1} Point on the Mechanical Properties of Carbon Steels.”

PEARCE, J. G.—“The Use and Interpretation of the Transverse Test for Cast Iron.”

PFEIL, L. B.—“The Change in Tensile Strength due to Ageing of Cold-Drawn Iron and Steel.”

REES, S. H.—“Some Properties of Cold-Drawn and of Heat-Treated Steel Wire.”

SWAN, J.—“The Effect of Silicon on Tungsten Magnet Steel.”

SWINDEN, T., and P. H. JOHNSON—“Chromium Steel Rails.”

TAPSELL, H. J.—“The Fatigue-Resisting Properties of 0.17 per Cent. Carbon Steel at Different Temperatures and at Different Mean Tensile Stresses.”

WESTGREN, A., G. PHRAGMÉN, and TR. NEGRESKO—“On the Structure of the Iron-Chromium-Carbon System.”

WHITELEY, J. H.—“Effects Observed in Quenched Liquid Steel Pellets and their Bearing on Bath Conditions.”

WOODWARD, W. E.—“The Rapid Normalising of Overstrained Steel.”

Volume XVII. of the Carnegie Scholarship Memoirs was published in 1928, and contained the following reports :

ARNFELT, F. H.—“ On the Constitution of the Iron-Tungsten and the Iron-Molybdenum Alloys.”

BRAMLEY, A., and G. TURNER—“ The Gaseous Cementation of Iron and Steel. Part IV.—The Action of Mixtures of Carbon Monoxide and Ammonia on Iron and Steel and its Bearing on the Process of Cementation.”

BRAMLEY, A., and F. W. HAYWOOD—“ The Gaseous Cementation of Iron and Steel. Part V.—Determination of the Iron/Iron-Nitride Eutectoid. The Action of Ammonia on Steels containing Different Concentrations of Carbon. Appendix.—Determination of the Iron/Iron-Carbide Eutectoid and the Solubility of Carbon in α -Ferrite.”

DEARDEN, W. H.—“ The Specific Heat of Iron below 400° C.”

O'NEILL, H.—“ Hardness and its Relation to the Cold-Working and Machining Properties of Metals. Part II.”

PARTRIDGE, J. H.—“ Electric and Magnetic Properties of Cast Iron.”

PUBLICATIONS.

The usual two volumes of the Journal, containing together 1546 pages, a volume of the Carnegie Scholarship Memoirs of 190 pages, and a List of Members (166 pages), have been published during the year.

ANDREW CARNEGIE RESEARCH SCHOLARSHIPS.

On the recommendation of the Carnegie Research Committee, grants were made by the Council during the year to the following candidates :

DAVID BINNIE (Glasgow), £100, to assist him in continuing his research work under Professor J. H. Andrew at the Royal Technical College, Glasgow, on behalf of the Heterogeneity Committee, the subject being the determination of the liquidus and solidus of carbon and alloy steels, and a study of reactions of sulphides in liquid and solid steels.

B. S. SMITH (Sheffield), £100, to assist the continuation of his research work under Professor C. H. Desch, F.R.S., at Sheffield University on behalf of the Heterogeneity Committee, the subject being the viscosity of molten steel.

HENRY TEMEL (Kladno, Czechoslovakia), £50, in aid of a research on the sulphur contents in slag of the open-hearth process.

JOSEPH VIETORISZ (Budapest), £50, in aid of an investigation on the properties of malleability of rolled or hammered iron and steel.

CARNEGIE GOLD MEDAL.

For the year 1928 the Carnegie Gold Medal was awarded by the Council to Dr. Arthur Bramley for his researches on the cementation of steel by various media.

WILLIAMS PRIZE.

In the year under review, two of the papers by authors qualified for consideration appeared to the Council to be worthy of an award, and accordingly it was decided to divide the prize between them as follows: To Messrs. J. E. Holgate and R. R. F. Walton, 50 guineas, for their paper on "Blast-Furnace Practice in Natal"; and to Messrs. A. Crooke and T. Thomson, 50 guineas, for their paper on "The New Plant of the Appleby Iron Co., Ltd.," both presented at the Annual Meeting.

LIBRARY.

During the year 1928 the Library has been enriched by the addition of 85 text-books, of which 37 have been presented, and the Council take the opportunity to extend their sincere thanks to the donors. Besides these over 450 pamphlets and over 300 different periodicals and Transactions of Scientific Societies have been received.

The upkeep of the Library involves an ever-growing expense, and the presentation of books and pamphlets dealing with iron and steel manufacture is most gratefully appreciated. The increasing demands made upon the Library for the loan of volumes and for research and inquiry is an indication of the value of the Library service to the members. During the past year about 650 volumes were sent out on loan.

TECHNICAL COMMITTEES.

The Technical Committees of the Institute have been prosecuting their studies during the last year, and have carried forward their labours to various stages of advancement. Committee No. 2 on Blast-Furnace Plant and Practice has presented a Report, which will be found in the present Journal.

Committee No. 5 has given further attention to the preparation and supply of new standard samples.

The Committee on the Heterogeneity of Steel Ingots has made progress, and a Third Report is published in this Journal.

By the co-operation of the Iron and Steel Institute with the National

Federation of Iron and Steel Manufacturers, a Committee was appointed during the year to study the problem of corrosion. The Committee has held several meetings, and has already made some headway with the work.

THE WORSHIPFUL COMPANY OF BLACKSMITHS.

In accordance with the understanding with the Wardens of the Company of Blacksmiths, applications for nomination for admission to the Company were invited, and Mr. W. J. Talbot of Walsall and Dr. G. E. K. Blythe of London have been recommended by the Council for admission to the Company.

APPOINTMENT OF REPRESENTATIVES.

The President continues to represent the Institute on the General Committee of the Royal Society for administering Government Grants for Scientific Investigations. Mr. M. Mannaberg and Mr. F. W. Harbord, C.B.E., represent the Institute on the Board of the National Physical Laboratory, and Sir Hugh Bell, Bt., C.B., performs a like office on the Board of Governors of the Imperial College of Science and Technology.

The Institute representatives on the Main Committee of the British Engineering Standards Association have been Mr. M. Mannaberg, Mr. B. Talbot, and Dr. W. H. Hatfield; on the Sub-Committee for Cast Iron, working under the direction of the Sectional Aircraft Committee, Mr. H. J. Yates and Dr. W. H. Hatfield; on the Sectional Committee on Cast Iron, Mr. H. B. Toy; on the Technical Committees of Motor Industries, Mr. J. H. S. Dickenson; on the Sectional Committee for Chemical Engineering, Mr. F. W. Harbord, C.B.E.; and on the Committee engaged in revising the British Standard Specifications for Conduits and Fittings for Electric Wiring, Professor T. Turner.

Mr. F. Clements is the Institute representative on Panel D, on Gas-Producer Trials, of the Institution of Civil Engineers. Professor T. Turner is the Institute's Delegate to the British Cast Iron Research Association. Sir Robert Hadfield, Bt., and Mr. Harbord represent the Institute on the Council of the British Refractories Research Association, and Mr. Harbord represents the Institute on the Alloys of Iron Research Committee, and on the Advisory Board of the Royal School of Mines. On the Committee on the Improvement and Development of Basic Slag, formed by the Ministry of Agriculture and Fisheries, the Institute is represented by Dr. A. Cooper, Mr. M. Mannaberg, Mr. G. Hatton, C.B.E., and Mr. B. Talbot; on the Grey and Malleable

Iron Research Committee of the Department of Scientific and Industrial Research by Professor T. Turner; on the Technical Committee of Lloyd's Register of Shipping by Lord Invernairn and Mr. W. Simons; on the Board of Governors of the School of Metalliferous Mining (Cornwall), as well as on the Advisory Committee for the Metalliferous Mining and Quarrying Industries, by Professor H. Louis. Mr. M. Mannaberg is the representative of the Council on the Council of the Institution of Fuel Technology.

Sir Robert Hadfield, Bt., represents the Institute on the British Association Fuel Economy Committee, on the Court of Sheffield University, and on the Home Committee for the University of Hong Kong; while Sir W. Peter Rylands acts similarly on the Court of the University of Liverpool.

Mr. F. W. Harbord, C.B.E., has been appointed to represent the Institute on the Mechanical Warfare Board called into being by the Army Council.

CHANGES ON THE COUNCIL.

At the Annual Meeting in May 1928 Mr. Benjamin Talbot was elected President of the Institute, and Professor Henry Louis has been nominated by the Council to succeed in the Presidency at this Annual Meeting of 1929.

Mr. John Craig, C.B.E., was elected Vice-President to fill the vacancy caused by Mr. Talbot's accession to the Presidency, and Mr. E. J. George has been elected a Member of Council to take the seat vacated by Mr. Craig.

In accordance with Byelaw 10, the names of the following Vice-Presidents and Members of Council were announced at the Autumn Meeting as being due to retire at the Annual Meeting, 1929.

Vice-Presidents—Mr. E. H. Saniter; Colonel Sir W. Charles Wright, Bt., K.B.E., C.B.; Mr. M. Mannaberg.

Members of Council—Mr. A. Dorman; Dr. W. H. Hatfield; Mr. V. B. Stewart, C.B.E.; Mr. H. Spence Thomas; Mr. A. O. Peech.

No other members having been nominated up to one month previous to the Annual Meeting, the retiring members, in accordance with the announcement made at the Autumn Meeting, are presented for re-election.

1929—i.

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BALANCE SHEET, DECEMBER 31, 1928—continued.

LIABILITIES.		ASSETS.	
Brought forward ...	£45,582 8 8	Brought forward ...	£45,582 8 8
Special Purposes Fund :—		Special Purposes Fund :—	
Capital Account, representing subscriptions received 1919-20 invested <i>per contra</i> ...	£9,451 0 0	£12,242 19s. 3d. 4% Funding Stock (1900-90) ...	£9,512 7 5
Income and Expenditure Account :—		Cash at Bank :—	
Balance at 1st January 1928 ...	£646 4 2	Current Account ...	1 8 1
Less Excess of Expenditure over Income for Year to 31st December 1928 ...	184 9 1	Deposit Account ...	399 19 0
Amount due to General Fund ...	461 15 1	• (The Market Value of this Security at 31st December 1928 was £10,988 1s. 2d.)	9,913 14 6
	19 5		
	3,913 14 6		
Williams Prize Fund :—		Williams Prize Fund :—	
Capital Account, representing the Market Value of £3,000 3½% Conversion Loan at 21st September 1926, when the Fund was inaugurated ...	2,220 0 0	£3,000 3½% Conversion Loan (at cost) ...	2,220 0 0
Income and Expenditure Account :—		Cash at Bank ...	163 17 6
Balance at 1st January 1928 ...	58 17 6	• (The Market Value of this Security at 31st December 1928 was £2,373 15s. 0d.)	2,383 17 6
Less Excess of Expenditure over Income for Year to 31st December 1928 ...	2 12 6		
Sundry Creditors—Prize Money ...	56 5 0		
Amount due to General Fund ...	105 0 0		
	2 12 6		
	2,383 17 6		
	£57,880 0 8		£57,880 0 8

SPECIAL PURPOSES FUND.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1928.

INCOME.		EXPENDITURE.	
To Interest on Funding Stock ...	£391 15 6	By Grants :—	
" Interest on Deposit ...	12 14 5	British Refractories Research Association ...	£25 0 0
	404 9 11	British Engineering Standards Association ...	50 0 0
		University College (Ramsay Memorial Laboratory)	52 10 0
		" Printing Report of Heterogeneity Committee ...	£127 10 0
" Excess of Expenditure over Income for the Year, carried to Balance Sheet ...	184 9 1	" Expenses of Heterogeneity Committee ...	176 5 0
	£588 19 0	" Subscription to International Testing Association ...	280 4 0
			5 0 0
			£588 19 0

GENERAL FUND.

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1928.

INCOME.			EXPENDITURE.		
To Entrance Fees	...	£279 6 0	By Salaries (including Overtime)	...	£3,338 1 0
" Annual Subscriptions :—	...	...	" Office Rent, Cleaning, &c...	...	... 1,063 13 3
Members—Home	£3,893 18 6	...	" Library Books and Binding	...	... 132 0 0
Do, Foreign	1,731 15 3	...	" Office Furniture and Fittings	...	... 31 16 0
Associates...	22 1 0	...	" Autumn Meeting	...	... 11 11 8
" Journal Sales	...	5,647 14 9	" Annual Meeting	...	... 141 3 4
" Interest on Investments, Less Tax :—	...	1,342 17 5	" Journal Publishing Expenses :—	...	...
General Fund	477 2 2	...	Printing, &c.	£2,014 8 1	...
Life Compositions Fund...	91 14 1	...	Abstracts	164 8 4	...
Bessemer Medal Fund	12 16 0	...	Postage	141 16 1	...
" Income Tax recovered	...	581 12 3	" Stationery and Printing (including copies of Papers)	2,320 12 6	...
(B.M. Fund)	...	3 4 0	" Postage and Receipt Stamps	493 3 11	...
" Surplus on Spanish Meeting Account	...	...	" Travelling Expenses	143 8 3	...
" Interest on Deposit	...	51 14 11	" Insurance	17 3 11	...
" Sale of Waste Paper	...	32 4 5	" Telephone Rental and Calls	21 11 1	...
" Sundry Receipts	...	1 5 8	" Auditor's Fees	28 12 3	...
	...	4 9	" Bessemer Medal	31 10 0	...
	...	...	" Compassionate Allowance	14 7 6	...
	...	...	" Office Disbursements and Sundry Payments	50 0 0	...
	...	...		78 19 4	...
	...	...		£7,917 14 0	...
	...	...		Excess of Income over Expenditure for the Year, carried to	...
	...	...		Balance Sheet	22 10 2
	...	...			£7,940 4 2

ANDREW CARNEGIE RESEARCH SCHOLARSHIP FUND.
INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1928.

INCOME.		EXPENDITURE.	
To Interest on Investments:—		By Scholarship Grants	£187 10 0
£2250 Newcastle-upon-Tyne Electric Supply		" Printing Memoirs	382 19 7
4½ per cent. Consolidated First Mortgage		" Postage of Memoirs	40 7 7
Debenture Stock		" Salaries	104 0 0
£7326 London & North Eastern Railway	£81 0 0	" Miscellaneous Printing and Sundries	1 0 6
4 per cent. Debenture Stock...	253 12 0		£715 17 8
£1312 London & North Eastern Railway			
4 per cent. 1st Guaranteed Stock	42 0 0		
£8750 London & North Eastern Railway		" Excess of Income over Expenditure for the Year, carried to	463 18 2
3 per cent. Debenture Stock...	210 0 0	Balance Sheet	...
£2000 London, Midland & Scottish Railway	64 0 0		
4 per cent. Debenture Stock	48 0 0		
£1500 Great Western Railway 4 per cent.	76 15 0		
Debenture Stock	80 10 0		
£2560 4s. India 5 per cent. Stock	39 16 0		
£2300 India 3½ per cent. Stock	75 8 4		
£1000 5 per cent. War Stock, 1929-47	£971 2 4		
£2693 12s. 3¼ per cent. Conversion Loan	5 3 8		
" Interest on Deposit	203 9 10		
" Income Tax recovered to 5th April 1928			
	£1,179 15 10		£1,179 15 10

"WILLIAMS PRIZE" FUND.
INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1928.

INCOME.		EXPENDITURE.	
To Interest on 3½ per cent. Conversion Loan	£84 0 0	By Printing Circulars	...
" Tax deducted from Interest, recoverable	21 0 0	" Prizes awarded during Year	...
" Excess of Expenditure over Income for the Year, carried to	2 12 6		£2 12 6
Balance Sheet	£107 12 6		105 0 0
	£107 12 6		£107 12 6

IRON, STEEL AND INDUSTRIAL FUEL; MONTHLY BULLETINS.
BALANCE SHEET, DECEMBER 31, 1928.

LIABILITIES.		ASSETS.	
Sundry Creditors :—		Sundry Debtor :—	
Printing Bulletins	£23 12 9	Iron and Steel Institute (General Account)...	£17 4 2
Grant re 1929 Issues :—		Cash at Bank	7 13 9
Received in Advance	1 5 2		
	<u>£24 17 11</u>		<u>£24 17 11</u>

IRON, STEEL AND INDUSTRIAL FUEL; MONTHLY BULLETINS.
INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED DECEMBER 31, 1928.

INCOME.		EXPENDITURE.	
To Grant from National Federation of I. & S. Mfrs.		By Bulletins Publishing Expenses :—	
" Subscriptions to Bulletins...	£252 14 10	Printing	£143 4 6
" Contributions re abstracts used in Journal of Iron and Steel Institute	33 0 0	Salaries	168 0 0
	33 2 8	" Administration :—	
		Salaries	6 0 0
		Miscellaneous	1 13 0
	<u>£318 17 6</u>		<u>7 13 0</u>
			<u>£318 17 6</u>

INVESTMENTS ON ACCOUNT OF GENERAL FUND OF THE INSTITUTE.

£1000 5 per cent. War Stock, 1929-47	...	...	...	...	...	£945 16 4
£549 19s. 2d. 3½ per cent. Conversion Loan...	...	...	...	...	...	409 11 0
£447 Southern Railway 4 per cent. Debenture Stock	...	...	...	...	...	449 2 4
£1872 London & North Eastern Railway 4 per cent. Second Guaranteed Stock	...	...	...	...	...	2148 13 3
£1872 London & North Eastern Railway 4 per cent. First Preference Stock	...	...	...	...	...	2148 13 4
£2241 London & North Eastern Railway 4 per cent. First Guaranteed Stock	...	...	...	...	...	2431 14 5
£437 London & North Eastern Railway 3 per cent. Debenture Stock...	...	...	...	...	...	376 12 5
£1500 Buenos Ayres Great Southern Railway 4 per cent. Debenture Stock	...	...	...	...	...	1594 12 9
£1000 Calcutta 4 per cent. Bonds, 1939	...	...	...	...	...	982 10 0
£800 Bombay 4 per cent. Bonds, 1939	...	...	...	...	...	809 0 0
£79 4s. 5d. "B" Annuity, Sclode, Punjab, and Delhi Railway	...	...	...	...	...	1999 0 7
£50 1s. 8d. "B" Annuity, Great Indian Peninsular Railway	...	...	...	...	...	1267 6 0
						<u>£15,562 12 5</u>

INVESTMENTS ON ACCOUNT OF LIFE COMPOSITIONS FUND.

£1330 London & North Eastern Railway 3 per cent. Debenture Stock	...	...	...	...	...	£1,254 17 6
£335 London Electric Railway, 4 per cent. Perpetual Stock	...	...	...	...	...	304 14 11
£335 Metropolitan District Railway 4 per cent. Prior Lien Debenture Stock	...	...	...	...	...	333 11 2
£376 London & North Eastern Railway 4 per cent. Second Preference Stock	...	...	...	...	...	371 0 8
£681 13s. 4 per cent. Funding Loan, 1960-1990	...	...	...	...	...	600 0 0
£160 14s. 2d. 3½ per cent. Conversion Loan	...	...	...	...	...	126 0 0
						<u>£2,990 4 3</u>

INVESTMENT ON ACCOUNT OF SPECIAL PURPOSES FUND.

£12,242 19s. 3d. 4 per cent. Funding Loan, 1960-1990	£9,512 7 5
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INVESTMENT ON ACCOUNT OF WILLIAMS PRIZE FUND.

£3000 3½ per cent. Conversion Loan	<u>£2,220 0 0</u>
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INVESTMENTS ON ACCOUNT OF ANDREW CARNEGIE RESEARCH SCHOLARSHIP FUND.

£2250 Newcastle-upon-Tyne Electric Supply 4½ per cent. Consolidated First Mortgage Debenture Stock	£2,261 10 0
£7925 London & North Eastern Railway 4 per cent. Debenture Stock	...	...	...	...	...	6,465 1 0
£1312 London & North Eastern Railway 4 per cent. First Guaranteed Stock	...	...	...	...	...	880 11 11
£8750 London & North Eastern Railway 3 per cent. Debenture Stock	...	...	...	...	...	5,611 2 8
£2000 London Midland & Scottish Railway 4 per cent. Debenture Stock	...	...	...	...	...	1,693 0 6
£1500 Great Western Railway 4 per cent. Debenture Stock	...	...	...	...	...	1,204 5 3
£2560 4s. India 3 per cent. Stock	...	...	...	...	...	1,525 3 3
£2300 India 3½ per cent. Stock	...	...	...	...	...	1,600 2 9
£1000 5 per cent. War Stock, 1929-1947	...	...	...	...	...	905 10 6
£2693 12s. 3½ per cent. Conversion Loan	...	...	...	...	...	2,006 19 0
						<u>£24,153 6 10</u>

(Signed) H. C. H. CARPENTER, *Hon. Treasurer*. G. C. LLOYD, *Secretary*.

I have examined the foregoing Balance Sheet and Income and Expenditure Accounts with the Books and Vouchers of the Institute, and certify them to be correct. I have also verified the Balances at the Bankers and the Securities for the Invested Funds shown above.

(Signed) W. B. KEEN, *Chartered Accountant*.

BESSEMER MEDAL FUND—(Trustees: Sir Hugh Bell, Bart., Lord Airedale, and Frank Samuelson, Esq.).
 £400 London Midland and Scottish Railway 4 per cent. Debenture Stock.

INDUCTION OF THE NEW PRESIDENT.

The PRESIDENT said he now had the pleasing duty of inducting his successor, Professor Henry Louis, M.A., D.Sc., into the Chair. Professor Louis was of international reputation. As a young man he worked at the puddling furnaces, the blast-furnaces, and also at a 10-ton steel furnace, which was thought very large in those days. Some of the other members did the same thing, and they certainly obtained experience, and possibly physical development, at the same time. He was sure that Professor Louis would receive not only the help of the Council but of the individual members, and that he would have a very successful term of office.

[The Chair was then vacated by Mr. Talbot, and taken, amid hearty applause, by the new President, Professor Henry Louis.]

Sir W. PETER RYLANDS, J.P. (Past-President), in moving "That the best thanks of the Institute be accorded to the retiring President for his services to the Institute during the past year," said it had been very pleasing to all of those keenly interested in the steel trade that Mr. Talbot should have occupied the Chair during the past year. Of all the Presidents of recent years he did not think there was one who had been quite so actively connected with the practical technical advancement of works practice in the steel trade as Mr. Talbot. His earliest recollection of Mr. Talbot as a member of the Institute was in regard to the papers he read on steel practice, furnaces, and sound ingots. He did not know whether Mr. Talbot had entirely solved the problem of how to produce an absolutely sound ingot, but certainly his papers upon the subject were most illuminating and suggestive, and, he had no doubt, marked an advance in that branch of their art and science. The members desired to thank Mr. Talbot for his services, and for the distinction and lustre that he had added to the office of President, which had been handed down to him from very many distinguished predecessors. He had very much pleasure in proposing that a hearty vote of thanks be accorded to Mr. Talbot for the work he had done for the Institute during the past year, and for the services he had rendered to all the members.

Mr. FRANK W. HARBORD, C.B.E. (Past-President), formally seconded the resolution, which was carried by acclamation.

Mr. BENJAMIN TALBOT (retiring President) thanked Sir Peter Rylands for the all too kind words he had used in reference to his services to the Institute. His work during the past year had been a labour of love, and he had enjoyed every minute of it. The Council and the individual members had been very helpful to him, and had made his work exceedingly easy. He thanked the members most sincerely for the cordial manner in which the resolution had been passed.

The PRESIDENT announced that the Council had sent to Sir Hugh Bell a message of sympathy for his recent long and serious illness. In reply the following telegram had arrived during the meeting :

“ Best wishes to the new President for successful period of office. I take this opportunity of thanking my colleagues of the Iron and Steel Institute for the kind sympathy they have expressed towards me during my illness. Sir Hugh Bell.” (Applause.)

PRESENTATION OF THE BESSEMER GOLD MEDAL TO THE
HON. SIR CHARLES PARSONS, O.M., K.C.B., F.R.S.

The PRESIDENT (Professor Louis) said the first official task allotted to the position to which the members had been good enough to elect him was the extremely agreeable one of presenting the Bessemer Gold Medal of the Institute to his distinguished fellow-townsmen, Sir Charles Parsons. It was a curious coincidence and peculiarly appropriate that on the Diamond Jubilee, the Sixtieth Anniversary of the foundation of the Institute, which had its origin in Newcastle-on-Tyne, the highest distinction which the Institute had in its power to award should go to a man whose work had been connected with Newcastle-on-Tyne. In such an assemblage it was entirely unnecessary—indeed it might almost be considered impertinent—to attempt to enumerate the very large number of services which Sir Charles had rendered to every branch of technology—services which covered everything from the manufacture of diamonds to that of steel ingots, from particles of microscopic dimensions to huge Atlantic liners. It was quite sufficient

to say that there was hardly an ironworks of any importance in the country in which a steam-turbine or a turbo-blower was not to be found at work. The brilliant work that Sir Charles Parsons had done had naturally brought him many, indeed he might even say most, of the distinctions that any man in his profession could covet ; but he ventured to think that, having regard to the long list of eminent men to whom the Bessemer Medal had been awarded in the past, even Sir Charles Parsons might take a pride in adding his name to so distinguished a roll, and the Iron and Steel Institute was certainly very proud that Sir Charles Parsons' name should appear upon it. It was unnecessary for him to say more on such an occasion, and it therefore only remained for him to hand Sir Charles Parsons the Bessemer Gold Medal, and to express the cordial wish that he might hold it, together with his many other distinctions, for very many years yet to come.

[The PRESIDENT then, amid hearty applause, presented the medal to Sir Charles Parsons.]

The Hon. Sir CHARLES PARSONS, O.M., K.C.B., F.R.S., tendered his sincere thanks to the Council for having presented him with the Bessemer Gold Medal, and expressed his profound sense of the great honour conferred upon him.

The Presidential Address was then delivered (see p. 29), and the following papers were read and discussed :

FIRST REPORT ON BLAST-FURNACE PLANT AND PRACTICE. By a Committee of the Institute.

E. H. LEWIS : " Twenty Months' Results of Dry-Blast Operation."

W. E. SIMONS : " The A.I.B. Sinter Plant at Messrs. Guest, Keen and Nettlefolds, Ltd., Cardiff Works."

R. H. GREAVES, H. H. ABRAM, and S. H. REES : " The Erosion of Guns."

H. SUTTON : " The Influence of Pickling Operations on the Properties of Steel."

G. A. HANKINS and Miss G. W. FORD : " The Mechanical and Metallurgical Properties of Spring Steels as Revealed by Laboratory Tests."

The Hon. Sir CHARLES PARSONS, O.M., K.C.B., F.R.S., and H. M. DUNCAN : "A New Method for the Production of Sound Steel."

THIRD REPORT ON THE HETEROGENEITY OF STEEL INGOTS. By a Committee of the Institute.

J. M. ROBERTSON : "The Microstructure of Rapidly Cooled Steel."

DARTREY LEWIS : "The Transformation of Austenite into Martensite in a 0.8 per Cent. Carbon Steel."

A. L. NORBURY : "Constitutional Diagrams for Cast Irons and Quenched Steels."

G. R. BOLSOVER : "Brittleness in Mild Steel."

L. B. PFEIL : "The Oxidation of Iron and Steel at High Temperatures."

E. G. HERBERT and P. WHITAKER : "The Differential Method for Measuring the Thickness of Hard Cases without Sectioning them."

T. E. ROONEY and G. BARR : "A Method for the Estimation of Hydrogen in Steel."

JUBILEE GREETINGS FROM OVERSEAS.

Mr. B. TALBOT (retiring President) read the following message which he had received from Mr. Charles M. Schwab :

"Please convey my congratulations to your Iron and Steel Institute upon their Diamond Jubilee, and also my good wishes to the gentlemen who have for so long been identified with it. I also send you these greetings as President of the American Iron and Steel Institute, for your kindly attitude to me still remains a warm and happy memory which I shall always retain. With best wishes for a delightful and a successful meeting—I am, Yours sincerely, Charles M. Schwab."

The PRESIDENT said the members would be interested to hear that the Institute had received cables from two gentlemen who were very prominent in their efforts to entertain the members at Bilbao the previous year, Señor Don Alfonso de Churruca and Count de Zubiria. Both those gentlemen congratulated the Institute on its Diamond Jubilee. The meeting would be glad to know their friends in Bilbao were keeping them in mind. (Applause.)

PRESENTATION OF CARNEGIE GOLD MEDAL TO DR. A. BRAMLEY.

The PRESIDENT said it was his very pleasant duty to present the Carnegie Gold Medal to Dr. Bramley. The medal was awarded

in respect of the Report which, in the opinion of the Council, was the most meritorious piece of research work presented in the course of the year by anyone working under the Carnegie Scholarship Scheme of the Institute, with the aid of a grant from the Carnegie Scholarship Fund. Dr. Bramley was an Associate of the Royal College of Science of South Kensington, and had taken his degree of Doctor of Science (London University) in 1916. Since 1919 he had been in charge of the Department of Pure and Applied Science at Loughborough College, Leicestershire. The first Report presented by him to the Institute had dealt with the gaseous cementation of iron and steel, which had been followed by further Reports on the diffusion of carbon and nitrogen into iron and steel. In all, Dr. Bramley had presented six Reports, which had all been printed in the *Carnegie Scholarship Memoirs*, and he was greatly to be congratulated on the high standard of metallurgical research work which had been attained by him in his capacity as chief of his Department at Loughborough College.

[The President then presented Dr. Bramley with the medal amidst hearty applause.]

Dr. BRAMLEY, in acknowledging the award, said he desired to take the opportunity of thanking all his associates who had helped him with the work. He could not have got through it without their most valuable assistance.

AWARD OF THE WILLIAMS PRIZE.

The PRESIDENT announced that the Williams Prize of 100 guineas, given for the best practical paper of the year, had been awarded in respect of a paper on Blast-Furnace Practice in Natal, written by Messrs. J. E. Holgate and R. R. F. Walton, who received 50 guineas, and 50 guineas in respect of another paper—on the New Plant of the Appleby Iron Co., Ltd.—by Messrs. A. Crooke and T. Thomson. Both of these papers were thoroughly practical papers, and, in the opinion of the Council, fulfilled the somewhat onerous, but very sound and sensible, conditions laid down by the donor of the prize. He had much pleasure in making the announcement. (Applause.)

CARNEGIE RESEARCH GRANTS.

The SECRETARY announced that applications for grants were received from nine candidates, and, after careful investigation of all the applications, the Council had decided that grants of the amounts shown below be awarded to the following applicants :

- R. H. ABORN (Cambridge, Mass., U.S.A.), £100, in aid of a research on the occurrence of oxygen in iron and steel and its influence, particularly on red-shortness.
- J. E. DANGERFIELD (Birmingham), £100, in aid of a research on nickel and silicon in whiteheart malleable cast iron, with special reference to thin-walled malleable.
- S. G. ERICSON (Stockholm), £100, to assist in determining directly the volume change occurring at the solidification of iron.
- A. L. NORBURY (Birmingham), £100, in aid of a research on the effects of special elements on the physical and mechanical properties of cast iron.
- H. O'NEILL (Manchester), £50, to assist in an investigation of the hardness of metals as determined by a method of "unrecovered" indentation measurement.

PRESIDENTIAL ADDRESS.

BY PROFESSOR HENRY LOUIS, M.A., D.Sc., &c.

MY first duty on taking this Chair is to render you my very heartfelt thanks for the honour you have done me in electing me to it ; highly though I value this honour, I must admit that I view with no little trepidation the duties which it is laying upon me. It is no light task to endeavour, as best I may, to tread in the footsteps of the long line of illustrious men who have preceded me in the Presidency of the Iron and Steel Institute—men whose example rises before me as I speak, and not a few of whom I have been privileged to know during the relatively long period in which I have been connected with this Institute, seeing that it is exactly fifty years ago that I read my first paper before it at a meeting made memorable by the fact that it was the occasion when Messrs. Gilchrist and Thomas communicated to the members of the Institute the epoch-making process which they had invented.

The changes which this half-century has wrought in the manufacture of iron and steel would of themselves present a fascinating theme, but I propose to-day, with your permission, to take a much wider range, and to put before you a short summary of the history of iron manufacture from its very beginning, viewed in the special light in which I venture to regard it—namely, as a consequence and corollary of the ever-increasing power which mankind gradually learnt to exercise over the production of heat. I hope to be able to show that the history of iron and the history of heat generation have gone hand-in-hand throughout the ages, and that the former has been absolutely dependent upon the latter.

It is, perhaps, an especially appropriate thesis for me to develop on account of my close connection with another great Institute, the Institution of Mining Engineers, the members of which are responsible for by far the greater portion of our output of that fuel which is nowadays almost the sole source of heat that has been pressed into the service of iron and steel manufacture.

The date and even the place of the first use of iron by mankind

have never been determined ; it appears to be generally held that it was first produced in workable quantity on the southern flanks of the Caucasus, and the date assigned is usually somewhere about 3000 B.C., though for my purpose both the place and the exact or even the approximate date are matters of but secondary importance. It is at any rate certain that, before iron came into use, the metallurgy of bronze was already highly developed. Articles of bronze of the Later Bronze Age show that the art of bronze-founding had already reached a high stage of perfection. The art of making cored castings was undoubtedly known, and it seems probable that even the *cire perdue* process had been invented. No doubt the simple reduction of metallic iron from its ores would have been well within the capabilities of these primitive metallurgists, but from the simple reduction of the metal to its fashioning into any useful form is quite a far step. Oxide of iron is reducible to the metallic state at a very low temperature, not exceeding 500° C.,¹ but the iron so produced is more or less pulverulent and useless for all practical purposes. To weld it into a coherent mass capable of useful application requires not only a considerably higher temperature, but for articles of any size a considerable body of heat. There seems to be little doubt that in the early days articles were occasionally forged from meteoric iron, but this operation would require quite as much heat as forging iron reduced from ore. The only information that we have as to the early means of producing the necessary heat is derived from Egyptian mural paintings. It is significant that all the earlier ones—for instance, one from the frescoes of Beni-Hassan² (Fig. 1), said to date from about 2500 B.C.—show men blowing up a fire beneath a crucible by means of mouth blowpipes made of reed and tipped with clay, and it is evident that with such rudimentary appliances only very small pieces of iron could be produced. In corroboration, it may be pointed out that at these very early times iron was evidently looked upon as a scarce and valuable substance ; in the Swiss lake dwellings,³ and at Hallstatt,⁴ in Austria, articles of bronze have been found inlaid with iron, thus

¹ H. H. Meyer, *Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1928, vol. x. p. 107.

² Wilkinson, "The Early Egyptians," vol. iii. p. 223.

³ R. Munro, "The Lake Dwellings of Europe," pp. 516, 542, 545.

⁴ "Archæologia," vol. lviii.

indicating that the latter metal was the more valuable of the two. The date of the Hallstatt articles is usually given as between 1000 and 875 B.C.¹ The Crown Prince of Sweden in his recent excavations at Nauplia, on the Bay of Tolon, Greece, found a silver ring in which was set a seal made of iron; this was found in a tomb together with a bronze dagger and other bronze articles, the date assigned being about 1100 B.C. The first known representation of any mechanical means for producing a blast is from the walls of a tomb of the period of Thothmes III.,² supposed to be from



FIG. 1.—Blowing Up the Fire by the Mouth Blowpipe (Egypt).

about 1500 B.C. This primitive bellows (Fig. 2) apparently consists of a flat pot covered with skin, in the centre of which is cut a hole that can be closed at will by the heel of the operator, which thus forms a valve, the skin, when released by the heel, being pulled up by a cord in the worker's hand. It is interesting to note that this identical type of bellows is still used in India by certain tribes for the purpose of iron manufacture, the only improvement in over 3000 years being the use of a couple of light bamboos which act as springs to pull up the hide cover. A photograph of a native lad working these bellows (Fig. 3, Plate I.), taken a few years ago by the late Mr. Seymour Wood, shows the method;

¹ Harold Peake, "The Bronze Age and the Celtic World," p. 118.

² Wilkinson, "The Ancient Egyptians," vol. iii. p. 339.

moreover, these bellows have been figured in full detail by Dr. John Percy in his classical work on the "Metallurgy of Iron and Steel."¹

Various other forms of bellows² are also in use in different parts of India. Another of Mr. Wood's photographs (Fig. 4, Plate I.) shows a man cleaving with an axe the lump of soft iron made by the above-described bellows; it is therefore certain that a furnace urged by such bellows can be used for reducing iron from its ores in masses of workable size. I am aware that



a, b, k, o, the leather case.

c, e, l, n, the pipes conveying the wind to the fire.

d, m, the fire.

h, q, charcoal.

k and *o* are raised as if full of air.

FIG. 2.—The Earliest Known Form of Bellows (Egypt).

some authorities maintain that iron was used in Egypt for industrial purposes before 2500 B.C.,³ but even if this were correct, it would be only in quite small pieces. In any case I would suggest that it could not have been much used before some means of readily producing the required blast had been devised; so far, all that can be said definitely is that such invention must have been prior to 1500 B.C., but no one can say how much earlier,

¹ P. 263, Figs. 4 to 10.

² See Percy, *op. cit.*, pp. 254-270. For a detailed description see paper by F. H. Wynne, *Transactions of the Institution of Mining Engineers*, 1903-1904, vol. xxvi. p. 231, with photographs taken in 1903 when Mr. Wynne, now Deputy Chief Inspector of Mines, was acting as my assistant.

³ *Journal of Egyptian Archaeology*, 1928, vol. xiv. p. 191.



FIG. 3.—Bellows as used in India.



FIG. 4.—Cutting a lump of direct-made iron in India.

[To face p. 32.]



FIG. 5.—Charcoal blast-furnace at Backbarrow in 1909.

though it does appear probable that it may have taken place between the years 2500 B.C. and 1500 B.C.

The position at a tolerably reliable date can be well estimated from the British Museum excavations at Djerabis on the Euphrates (the Carchemish of Biblical times); as recorded in Biblical writings and elsewhere, this place was the scene of fighting between the Babylonians and Egyptians as early as 604 B.C.¹ The finds consisted of broken swords and spear-heads, all of bronze, and of numerous arrow-heads, both of bronze and of iron; there was also found a beautifully finished bronze mould for casting the bronze arrow-heads, and it is particularly noteworthy that these bronze arrow-heads are far superior in execution and finish to the iron ones—the iron ones being all tanged, whilst most of the bronze arrow-heads are socketed. The fact of finding the bronze mould is clear evidence that bronze arrow-heads were used by the defending force—that is, by the Egyptians, or more probably by their Hittite allies²—though it is impossible to say that they did not also use iron ones, neither is there any definite evidence as to the type of arrow-head used by the Babylonians, who may have had either bronze or iron, or both, as far as the evidence from the finds goes. It is therefore evident that at this date, even in the centre of the highest civilisation of the time, skill in working iron had not reached anything like so high a level as that of the bronze-worker; the finds are, of course, not conclusive evidence that no larger weapons of iron were in use at the time, but I think that the conclusion may fairly be drawn that they must have been far scarcer than the bronze weapons, and that the difficulty of working even moderately large pieces of iron had by no means been fully overcome, and that whilst small articles of iron could be made readily enough, there must still have been difficulty in producing the larger articles which required a considerable body of heat. This emphasises the essential point which I want to bring out, that the means of generating the requisite heat must have been the controlling condition in the manufacture

¹ See 2 Chronicles xxxv. 20–24, and Jeremiah xlv. 13–26; also Wilkinson, "The Ancient Egyptians," 1836, vol. i. p. 163. The "Encyclopædia Britannica" states that Nebuchadnezzar attacked and captured Carchemish in 605 B.C. A wall-case label in the British Museum reads: "Objects found in the ruins of a large house in the outer town of Carchemish destroyed in 604 B.C. when Nebuchadnezzar defeated Pharaoh Necho who had occupied the town."

² Private communication from Mr. C. Leonard Woolley.

of iron. Furthermore, as is well known, whilst iron reduced at a low temperature, even from impure ores, is sufficiently pure not to be brittle, it must necessarily be very soft, and it may readily be supposed that a well-made bronze sword was for quite a while superior to a soft iron one. This difficulty must have persisted until a much later date in Northern Europe, since the Norwegian Sagas ¹ more than once record that a warrior had a sword so soft that he had to stop to straighten it underfoot in the course of the conflict. It would appear to be probable that a good deal of the earlier iron made in Northern Germany and Scandinavia must have been reduced from bog iron ores ; these ores are usually high in phosphorus, and the reduction must have taken place at quite a low temperature and, therefore, have produced a very soft iron.

On the other hand, it is quite certain that in the countries bordering on the Mediterranean, where the knowledge of metallurgy was much older and civilisation was much further advanced, temperatures high enough to cause some carbon to combine with the iron and thus make relatively low carbon steel or steely iron had been attained at a very much earlier date, as is evident from the oft-quoted passage in Homer's *Odyssey* ² ; from this it is obvious that steel or steely iron capable of being hardened by quenching was known in Homer's time, though the carbon content could not have been excessive, seeing that the metal so treated was not too brittle to prevent its being used as an axe ; yet there must have been enough carbon present to cause perceptible hardening by quenching, seeing that Homer states that such quenching gives strength to the iron. On the other hand, Homer's frequently repeated epithet for iron "wrought with much toil" ³ shows that the manufacture of iron was still in an elementary stage ; it will be remembered that Homer certainly wrote before 800 B.C.

It could, however, not have been very long after the beginning of our era before, with the employment of larger furnaces and, therefore, the production of a greater body of heat, a true steel

¹ See, for instance, the account of one of the fights of Steinthor of Ere about A.D. 997 : "Eyrbyggja Saga" (the Saga Library, vol. ii. p. 120) ; also, a fight of Kjartan Olafsson, about A.D. 1000 : "Laxdæla Saga" (translation by M. A. Press, p. 177).

² "Odyssey," Book IX., line 391 *et seq.*

³ σίδηρος πολύκιμος. "Iliad," VI., 48 ; X., 379 ; XI., 133.

was produced, and this would, of course, be the case more readily when manganiferous ores happened to be employed instead of ordinary iron ores. Thus both Horace¹ and Ovid² refer in their poems to the high quality of Noric iron. The Noric kingdom corresponded to the region now known as Styria and Carinthia, and it is quite probable that this Noric iron was made from manganiferous spathic iron ores of the Styrian Erzberg of Eisenerz.³ Jars,⁴ who visited the Erzberg in 1758, calls attention to the fact that steel was readily produced by smelting certain of these ores. Similar ores appear also to have been worked in Spain, and they, too, must have produced steel or steely iron, and we have evidence that some at any rate of this material consisted of iron combined with sufficient carbon to be capable of being appreciably hardened by quenching. It must be remembered that the above statements as to the use of iron refer only to the region which at that early date was the centre of human civilisation; it is generally held that iron was not introduced into Britain until 500 B.C., and that its manufacture did not commence in these islands until about a century later.

Before Caesar's invasion, iron was certainly being made in the South of England, though the Brigantes in the North⁵ appear still to have been in a Stone Age. Before Caesar's time, iron currency bars⁶ were in use in Southern Britain—a fact which would seem to imply that, although iron was being made, it was still scarce and comparatively valuable. After Britain had become a Roman province, iron was made at numerous places in this country, most actively perhaps in the Forest of Dean, though there were various other important centres of early Roman iron production. The manufacture of iron continued in this country throughout the Roman occupation. The largest mass of Roman iron found in this country, if not in the world, is the mass discovered at Corstopitum, near Corbridge, in Northumberland, described by Sir Hugh Bell.⁷ Its date is considered to be between

¹ "Epodon," ch. 17, line 71; "Odes," Book II., ch. 16.

² "Metamorphoses," Book XIV., line 712.

³ H. Bauerman, "Erzberg of Eisenerz," *Journal of the Iron and Steel Institute*, 1907, No. III., p. 27.

⁴ "Voyages Métallurgiques," vol. i. p. 30.

⁵ J. Newton Friend, "Text-Book of Inorganic Chemistry," vol. ix., pt. 2, p. 3.

⁶ J. Newton Friend, *Transactions of the Worcestershire Naturalist Club*, 1919, pt. 2.

⁷ *Journal of the Iron and Steel Institute*, 1912, No. I. p. 118.

A.D. 350 and 380. and its weight was about 3 cwt. It is interesting to note that the famous iron pillar of Kutub, near Delhi, dates from about the same period or a little earlier, but weighs no less than some 6 tons, so that at that date the Eastern iron makers were far ahead of their Western contemporaries. There is, however, no doubt that both of these masses of iron were produced by the same method, that of making relatively small lumps of iron by the direct process and welding them together. It is quite clear that the method of iron production throughout all this period was always the same—namely, direct reduction by charcoal in furnaces probably not more than 3 ft. or 4 ft. high, and blown by bellows worked by man power, in which the temperature was only high enough to produce soft malleable iron, or, at the best, with suitable ores a steely iron or a steel. Apparently this method of iron-making must have continued during the next thousand years or so; probably furnaces were steadily increasing in size, larger lumps of iron were being made, and probably steely iron or even steel was produced at will. The art of letting down or tempering steel must also have been discovered, and the technique of iron working, as distinct from the extraction of iron, made immense strides.

An invention that must have contributed no little to the increase in the size and power of the mediæval furnace was that of mechanical blast production. Agricola, whose well-known work is dated 1556, though he himself died in the previous year, figures and describes in much detail the construction of a bellows with valves of quite modern type, worked by a water-wheel,¹ and it is obvious from his description that the appliance was old enough for its details to have become standardised. It is on record that such bellows were in use at Göllnicz² in 1435. A natural result of the increase in the height and power of the furnace and of the attendant higher heats thus generated was the production of white cast iron, and it is tolerably clear from Agricola's writings that this was known in his day. No doubt this unexpected result of the higher furnace temperature must have been a disagreeable surprise to the early metallurgist, who found in his furnace a lump of this hard, brittle, useless material

¹ "De Re Metallica," Book XII.

² "Iron Ore Resources of the World," vol. i. p. 178.

instead of the mass of malleable iron or steel which he hoped to produce. In the course of time, however, he would discover that this useless metal could have its pristine malleability restored to it, or, as he expressed it, the iron could be "freshened" by heating it in another (or possibly the same) furnace. Naturally, at that period the fact that the white iron was simply highly carburised, and that the freshening process consisted in burning out its carbon, could not have been even suspected, but when this technical stage had been reached the iron-worker no doubt soon learnt to appreciate the advantage of a continuous process in which the metal could be made to flow out from his reduction furnace, over a discontinuous process in which the lump of metal had to be dragged out of the furnace either by tearing down the furnace front or by lifting the lump bodily out of it. This step would lead to a still further increase in furnace and bellows capacity, and this in turn would bring about a further increase in furnace temperatures, with the again unexpected result of producing grey cast iron, as soon as the temperature became high enough to reduce sufficient silicon. It would soon be found that such iron ran very fluid and was admirably adapted for making castings. Apparently one of the very earliest forms of iron castings was the iron stove plate, which originated in Germany. A sketch is known, from which a stove plate was evidently intended to be cast, dated 1474, in Nassau,¹ though the plate itself has not been found. The oldest known cast-iron stove plate is dated 1497 and was from the Eifel,² which appears to have been one of the earliest centres at which castings of this kind were made. No doubt it took the early founders some time before they learnt to adapt their bronze-founding technique to this new material, very much in the same way as in our own time iron-founders have had to learn to modify their methods for the successful production of steel castings; but the superior qualities of articles made of cast iron would be a sufficient incentive to urge these early workers to find out how to overcome their difficulties. Once this was done, a demand for such pig iron would arise and the blast-furnace making charcoal iron was evolved. The next step was the substitution of coke for charcoal, thus attaining the production of still higher

¹ E. Schrödter, *Stahl und Eisen*, 1914, vol. xxxiv. p. 1075.

² A'brecht Kippenberger, "Die Kunst der Ofenplatten." Düsseldorf, 1928.

temperatures; it is, by the way, interesting to note that the first coke furnaces still used bellows worked by a water-wheel, just as in Agricola's time, and that these continued in use up to the middle of the eighteenth century.¹ About that date they were, however, replaced by iron blowing cylinders, capable of generating a more powerful blast, and, therefore, of producing higher temperatures, whilst Neilson's invention of the hot-blast in the year 1828 enabled still higher temperatures to be attained in the blast-furnace.

The next stage was the production of mild steel in the Bessemer converter and the Siemens open-hearth furnace, to be followed by the important modification of Thomas and Gilchrist, which we know as the basic process. Necessarily, these processes involved the use of still higher temperatures than had hitherto been attained, and finally we reach the production of alloy steels in the electric furnace with its capacity for generating still higher temperatures.

I do not wish to imply that each one of these successive stages immediately and definitely put an end to all use of the earlier processes. Quite the contrary is the case, for there are many examples of the old and new methods working side by side. Furthermore, it is quite probable that small articles of steel, and perhaps even of cast iron, may have been produced sporadically and more or less accidentally, long before the regular manufacture of these materials, on what may be called an industrial basis, had become established. Probably the first furnace in which cast iron was thus produced was the mediæval German *Stückofen*, and it seems that in this furnace either malleable iron or cast iron could be produced,² though it is not clear that the mediæval smelter understood how to produce either the one or the other at will. Even to-day in India and in many other semi-civilised countries the direct process is still in use. Although cast iron was produced at least as far back as the fifteenth century, the Catalan³ direct process survived in the Pyrenees until at any rate the middle of the nineteenth century, and I have seen a direct process in operation in the Adirondacks, on Lake Champlain, in 1879. Again, although Abraham Darby successfully made pig iron with mineral fuel as far back as the year 1735, charcoal blast-furnaces are still in operation in Sweden and various other

¹ Percy, "Metallurgy of Iron and Steel," p. 889.

² *Ibid.*, pp. 319, 326.

³ *Ibid.*, p. 278.

parts of the world, and there was even one still at work in this country until quite recently at Backbarrow, near Ulverston; this little furnace (Fig. 5, Plate II.) used cold-blast as recently as the year 1909, when I, as consulting engineer to the company owning it, put in an iron pipe stove for heating the blast, and it was making charcoal iron until it was changed over to cold-blast coke pig iron on December 17, 1925. In spite, however, of this overlapping of processes and of the survival of the older methods alongside of newer ones, the line of progress is quite unmistakably defined.

One interesting fact emerges from this review—namely, that each successive metallurgical advance has been attended by a deterioration in quality of the product (except in cases when an entirely new material has resulted), though each has been accompanied by such an increase in quantity of output as to more than compensate for the inferior quality, by placing increasing quantities of iron at the service of mankind. It is only necessary to compare the blast-furnace of 1750, which, according to the records of the time, was doing excellent work when it produced 24 tons per week, with the modern furnace which smelts that quantity in about half an hour. On the other hand, it is undeniable that puddled iron is inferior to iron made by the direct process, that coke pig iron is inferior to charcoal pig, and that hot-blast pig iron is not as good as cold-blast pig. Again, whilst structural steel was in one sense an entirely new material, from another point of view it is not unfair to say that it is an inferior material to the older crucible steel. Nevertheless, it is also undeniable that the world is distinctly the richer for having at its command the huge quantities of iron and steel that were quite unthinkable even a century ago.

It will, I hope, be admitted that this rapid review of the history of iron manufacture is correct, at any rate, in its main features, and that my contention, that the power to produce high heats has throughout been the controlling factor, is well founded; I want to make it clear that I consider that the various stages of iron manufacture and of the generation of ever higher temperatures are not two independent concurrent parallel lines along which the development of human civilisation has travelled, but that they are distinctly related as cause and effect. This being true of the past, what can we say as to the future? Just as there

is a lower heat limit below which iron capable of being usefully applied in the arts could not be produced, so there must be an upper limit, and I suggest that this limit is reached when our furnaces are capable of generating a temperature sufficient to volatilise the iron ; it seems fairly obvious that heats higher than this cannot well be usefully employed. Such heats are, however, now readily attained in the electric furnace, and it would, therefore, seem that from this point of view the limiting condition has already been reached by the metallurgist. On the other hand, there seems but little inducement to increase the quantity of output, seeing that our potentialities of production appear to be now actually ahead of the world's requirements, and that there is every indication that even our present appliances will enable us to keep pace with any future demands.

I emphatically do not mean to imply that we have reached finality in the metallurgy of iron, but I do hold that future progress will have to be along different lines. Fortunately, we are already able to see what direction this progress must take. Recent advances have all been in the direction of improvement in quality and in the attainment of properties in which ordinary iron by itself is deficient, such as we have already obtained by the use of alloy steels, of which Sir Robert Hadfield may well claim to be one of the pioneers. In other words, the future of the metallurgy of our metal will be directed, not by the crude methods of trial and error of the past, but by the application of principles developed by the methods of scientific research. For something like four centuries this country has led the way in the great improvements in the iron industry along the old lines which I have been describing ; we are, however, also the inventors of the science of metallography, and alloy steel, with its numerous possibilities, of which high-speed tool steel may be quoted as an example, has also originated here ; we may, therefore, fairly claim that even in modern scientific methods we are equally leading the world in the metallurgy of iron, and there is every reason to presume that the great work which the members of this Institute have done in the past in developing that iron industry which is the basis of our modern civilisation will still continue in the future, although, as I have suggested, that work will be carried on by means of modern methods and be based upon entirely different principles.

VOTES OF THANKS.

To the President for his Address.

Sir ROBERT HADFIELD, Bt. (Past-President), said that, as senior Past-President, he had the pleasure and honour of proposing that a hearty vote of thanks be accorded to the President for his admirable Address. He doubted whether any previous Address had had packed into it so much valuable information in such a brief form, and the members were deeply indebted to the President for the care he had taken in preparing it. The Presidential Address was not open to discussion, but he would like to add a few remarks to those the President had made with reference to the most interesting specimen of iron in the world, the Delhi pillar. The members would probably remember that, as he stated in the paper he read before the Institute, he was the possessor of a small sample of that pillar, which he had been able to analyse; the iron was of 99·88 per cent. purity, a very excellent performance in view of the crude methods adopted in the days when the pillar was made. He was glad that the President had reminded the members that the Delhi pillar did not weigh more than 6½ tons, although it must be remembered that that was a very large weight when the date at which it was produced was kept in mind. He had much pleasure in proposing that a very hearty vote of thanks be accorded to the President for his excellent Presidential Address.

Mr. G. H. STRICK (Cheltenham) said that, as one of the seventeen members whose names had been on the roll of the Institute for between 50 and 60 years, he desired to second the resolution of thanks to the President for his admirable address.

The resolution was carried by acclamation.

The PRESIDENT, in reply, thanked Sir Robert Hadfield for the very kind remarks he had made, and the members for the equally kind manner in which they had been received. The address was somewhat on the usual lines, but he had always been fond of delving among old records, and he had always thought that the best way of finding out where one was going to was to look back on the road along which one had come.

To the Institution of Civil Engineers.

The PRESIDENT'S motion, that a cordial vote of thanks be accorded to the Institution of Civil Engineers, who once again had put their magnificent facilities at the disposal of the Institute, was carried by acclamation.

To the President.

Professor H. C. H. CARPENTER, F.R.S. (Hon. Treasurer), in proposing a hearty vote of thanks to the President, said that those who knew Professor Louis no doubt felt, when he was elected President, that he would fill the Chair and carry out its duties worthily. The Institute had received ample proof of that during the two days the President had occupied the Chair. Professor Louis had delivered a most interesting Presidential Address, and had presided with great distinction at the Annual Dinner. He had shown the greatest courtesy in the Chair. The present meeting had been memorable in many ways. Papers had been presented which were of quite exceptional importance. He hoped Professor Louis would look back on the past two days with as much pleasure as would the members of the Institute generally.

The vote of thanks was carried with acclamation.

The PRESIDENT, in thanking the members for their expression of appreciation, said that quite honestly he could claim to have been a good chairman, because the function of the chairman was not to make speeches himself, but to get good papers presented, and in that respect he had been very fortunate and successful.

The proceedings then terminated.

ADDITIONAL MEETING HELD IN GLASGOW.

Thursday, May 9, 1929.

An additional meeting, held jointly with the West of Scotland Iron and Steel Institute, took place in the Royal Technical College, Glasgow, on Thursday, May 9, at 7 P.M. Mr. Robert Hamilton, Senior Vice-President of the West of Scotland Institute,

took the Chair. Nearly forty members were in attendance. Mr. Hamilton extended a welcome to the members present and explained briefly the objects of the meeting. It had long been felt by the Council that many members of the Institute, owing to their residence at a considerable distance from London, were debarred from taking part in the proceedings of the Annual Meetings which, in accordance with long-standing custom, were always held in the latter city. To meet that difficulty, the Council had embarked on the policy of holding additional meetings in the various districts where a large body of members were concentrated, in order to provide an opportunity for the further discussion of any papers of special interest presented at the London meeting. A further object of holding such meetings was to encourage new members to join the Institute. He expressed his pleasure at seeing so many of the members present on this first occasion of holding an Additional Meeting in Glasgow, and hoped that the new movement would be attended with every success.

The following papers were presented and discussed :

- (a) The Hon. Sir CHARLES PARSONS, O.M., K.C.B., F.R.S., and H. M. DUNCAN : " A New Method for the Production of Sound Steel."
- (b) THIRD REPORT OF THE COMMITTEE ON THE HETEROGENEITY OF STEEL INGOTS.
- (c) E. H. LEWIS : " Twenty Months' Results of Dry-Blast Operation."
- (d) W. E. SIMONS : " The A.I.B. Sinter Plant at Messrs. Guest, Keen and Nettlefolds, Ltd., Cardiff Works."
- (e) FIRST REPORT OF THE COMMITTEE ON BLAST-FURNACE PLANT AND PRACTICE.

At the conclusion of the meeting, Mr. Hamilton proposed a vote of thanks to the Authorities of the Royal Technical College for the use of their rooms, and a vote of thanks having also been passed by the meeting to Mr. Hamilton for his kindness in presiding, the proceedings terminated.

ADDITIONAL MEETING HELD IN SHEFFIELD.

Wednesday, May 15, 1929.

An additional meeting, at which over sixty members and their friends were present, was held in the Mappin Hall of the University

of Sheffield on Wednesday, May 15, at 2.30 P.M. Professor C. H. Desch, F.R.S., Dean of the Faculty of Metallurgy in the University, and Member of Council of the Iron and Steel Institute, took the Chair.

Sir HENRY HADOW, C.B.E. (Vice-Chancellor of the University), offered the Institute a very cordial and hearty welcome to Sheffield in this most auspicious year of its history, the year of its Diamond Jubilee. He did so with the more pleasure, because the President this year was a very old and valued friend of his. He understood that the additional meetings had been arranged on the ground that at any rate in Sheffield and in Glasgow not less worthy fields and opportunities of discussion would be found; he was glad to recall that two of the papers for consideration were presented by members of Sheffield University. He hoped most sincerely that the collaboration of Sheffield University with the Iron and Steel Institute would always continue. He most sincerely asked the members to believe that he and his staff were very glad indeed to see them, and he hoped that the University of Sheffield, one of whose ideals was to serve as a whetstone for sharpening Sheffield blades, would be a venue in which the Institute could continue its discussions to its own great profit and to the advantage of the world at large.

Professor C. H. DESCH, F.R.S., speaking in the dual capacity of Professor in the University and Member of Council of the Institute, desired to express on behalf of the meeting its thanks to the Vice-Chancellor for his kind words of welcome, and for the trouble he had taken in coming down to the meeting.

The following papers were presented and discussed :

- (a) The Hon. Sir CHARLES PARSONS, O.M., K.C.B., F.R.S., and H. M. DUNCAN : " A New Method for the Production of Sound Steel."
- (b) THIRD REPORT OF THE COMMITTEE ON THE HETEROGENEITY OF STEEL INGOTS.

At this point the meeting adjourned for half an hour and partook of tea and light refreshments generously supplied by the

University Authorities. The meeting was then resumed, and the four remaining papers on the programme were discussed :

- (c) G. A. HANKINS and Miss F. W. FORD : " The Mechanical and Metallurgical Properties of Spring Steels as Revealed by Laboratory Tests."
- (d) L. B. PFEIL : " The Oxidation of Iron and Steel at High Temperatures."
- (e) G. R. BOLSOVER : " Brittleness in Mild Steel."
- (f) H. SUTTON : " The Influence of Pickling Operations on the Properties of Steel."

At the conclusion of the meeting, Dr. W. H. HATFIELD (Member of Council) said he had been asked to propose a vote of thanks to the University Authorities for their hospitality, and he had no doubt the meeting would be very glad to support that motion. He desired to say, quite frankly, on behalf of the Iron and Steel Institute, that the object of holding meetings in the Provinces was really to increase its membership. It was of first-rate importance to Sheffield, and, he hoped, to each one of those present, that the Iron and Steel Institute was really trying hard to build up and extend the science of metallurgy. If each member would make it his objective to secure one new member, that would help to increase the wealth of the Institute, which in turn would then have larger resources available for use in research. He had great pleasure in putting to the meeting a hearty vote of thanks to the University Authorities for their pleasant hospitality, and to Professor Desch for his kindness in occupying the Chair.

The resolution was carried unanimously amid applause.

The CHAIRMAN (Professor C. H. Desch, F.R.S.) wished to say, on behalf of the University Authorities, that they were very glad indeed to be able to offer hospitality to such an Institution as the Iron and Steel Institute, and on his own behalf he thanked Dr. Hatfield for his kind remarks. He was anxious to support what Dr. Hatfield had said about the desirability of an increased membership. There was already in Sheffield a considerable membership, but an even larger one was needed.

FIRST REPORT ON BLAST-FURNACE PLANT AND PRACTICE.

By COMMITTEE No. 2 OF THE IRON AND STEEL INSTITUTE.¹

FOREWORD.

DEVELOPMENTS in blast-furnace practice and plant during recent years have been rather in the direction of details of design and refinements in the application of principles and features already adopted as standard practice, than in the adoption of any new principles or methods, either of a radical or semi-radical nature.

In general, the trend in the United States is in the direction of larger, and still larger, furnaces with ever-increasing output capacities, from which, together with improved details in methods and equipment, and attention to details of management, considerable progress in economy of production has been attained, both in fuel consumption and in other items of production costs; whereas in Germany the attainment of similar ends has been sought by careful attention to the selection and preparation of materials, by sizing or sintering their ores, and sizing and screening limestone and coke, thus obtaining, through the greater permeability of the furnace charge and consequent economical increase in rate and efficiency of operation, improved economy of production and increased output per unit of hearth area.

Practically all those features, constituting more or less recent improvements in details, upon which the Committee has thus far been able to obtain information, are such as have been already referred to in the *Proceedings* of technical societies or in the technical press. The Committee, therefore, finds some difficulty in its search for any novel advance or general improvement in modern blast-furnace practice and plant, and is of opinion that in order to ascertain what, if any, more recent and as yet unpublished improvements may have been adopted in this field, and to obtain any information relative to them, it would be

¹ The Committee is constituted as follows: Messrs. A. K. Reese, Chairman, G. Barrett, A. Croke, E. H. Lewis, P. List, D. E. Roberts, and H. E. Wright.

necessary to appoint a small body of qualified investigators, who should be authorised to make visits to the more advanced iron-producing districts, at home and abroad, for the purpose of gathering new information and of formulating a report thereon.

For the present, and pending any further information which may be obtainable by the means above suggested, the Committee has prepared, and presents herewith, a Report outlining the various features of modern blast-furnace practice and plant, with short comments thereon and with references to some of the more recent methods devised for applying the principles, and attaining the purposes, aimed at under these headings.

The Committee fully recognises that this Report contains little, if any, information which has not previously been available from other sources to those who are interested and endeavour to keep themselves acquainted with the technical progress made in the iron industry; on the other hand, further emphasis will have been laid upon the importance, from the competitive standpoint, of the adoption of modern blast-furnace practice and plant by those who have not adopted those economic features which have become practically standard among their competitors.

In dealing with features pertaining to blast-furnace practice, and any recommendations bearing thereon, it is to be understood that they refer to that practice which includes the operation of each furnace, in any group of furnaces constituting a blast-furnace plant, as an individual unit; and that each furnace is blown with a definite and regular volume or weight of blast per minute, irrespective of variations in pressure due to varying conditions within the blast-furnace.

(The modern tendency towards the provision of the greatest possible uniformity in all materials and conditions affecting blast-furnace operation has led, as a further step in that direction, to the adjustment of the volume of blast blown, by periodic variation of the volume to allow for changes in atmospheric temperature, humidity, and pressure, for the purpose of providing the furnace with as regular as possible a weight of oxygen in the volume of blast supplied per minute.

This practice tends to minimise these irregularities in the rate of driving, and in quantitative reactions, which accompany the variations in the oxygen content per cubic foot of a con-

stant blast volume, due to changes of temperature, humidity, and pressure in the natural atmosphere which are so marked between daytime and night, and, at times, from hour to hour.)

With modern blast-furnace practice and plant it is considered that the following three objects are those which it is desired to attain :

1. Regularity in that quality of product required for the time being,
2. Maximum economy of production, and
3. Maximum output per unit of time,

the importance of these objects being in the order in which they are named.

With modern blast-furnace plant and practice the various features involved therein are so interwoven in their effect that it is their composite result which must be considered as producing the highest degree of efficiency in each of these aims—*i.e.* that the adoption of no one of the features of modern practice and plant is sufficient in itself to yield the most satisfactory results in that direction which appears to be the particular function of that feature; in fact (as has been too often experienced), such adoption may yield very little, if any, material improvement.

The various factors entering into the subject under consideration may be enumerated as follows :

Selection of raw materials.

Preparation of materials.

Mechanical handling of materials.

Furnace charging and top distribution.

Furnace lines (interior).

Hot-blast stoves.

Gas cleaning.

Gas burning and surplus gas.

Blowing plant.

Power plant.

Dry blast.

Pig iron casting.

General layout of plant.

Use of recording instruments in connection with the operation of the blast-furnace.

Oxygen enrichment of blast.

SELECTION OF RAW MATERIALS.

In selecting material for blast-furnace use, the quality, as determined by chemical analysis, is of considerable importance, and has necessarily a direct and marked influence upon the results obtained, and even upon the design of the plant to obtain them. Local and commercial considerations, however, are always vital factors in this connection, and such considerations alone decide whether the cost of material of higher grade may outweigh the advantages of its use, or, conversely, whether it is worth while suffering the drawbacks connected with the use of low-grade material which can be delivered to the furnaces at a low cost. Hence it is extremely difficult to be definite upon questions of quality, and it is only proposed to deal with the matter on broad lines.

The general opinion of those operating blast-furnaces undoubtedly favours strong coke of open texture. Although there are odd exceptions, it is a general rule that as the ash in coke increases beyond 10 per cent. the coke shows an increased tendency to brittleness, and, on this account, its general character is liable to fall below the best standard. Where the selection of fuel is practicable this point should be borne in mind. It is, moreover, generally accepted that in the case of all furnaces, excepting possibly those using particularly high yielding ores, an increase of 1 per cent. of ash in round figures is equal to a 2 per cent. decrease in coke value, due to the necessity of melting the ash which has replaced 1 per cent. of carbon in the coke.

The practical point of view upon a more indefinite question—namely, that characteristic which has been termed the reactivity of coke to carbonic acid—is that the loss of carbon by such reactivity in the upper portion of the furnace, where carbonic acid exists in large proportions in the gases, may counterbalance any virtue such coke may have by reason of its combustive reactivity on reaching tuyere level. Practical experience also indicates that, in its descent of the furnace, the reactivity of the coke is somewhat affected by carbon deposition, which makes it at least doubtful whether tests on the reactive quality of coke as charged have any direct bearing on the state of the same coke when it reaches the lower combustive area. The research which

is being made into coke quality by the various Coke Research Committees may with advantage be encouraged until knowledge upon this and other points is more definite.

In regard to selection of ore by analysis, &c., there is every indication that the better blast-furnace results are associated more with high yielding (and more especially with high yielding, easily reducible ores) than with low yielding varieties. On the other hand, where furnaces use ores of indifferent quality the results are almost invariably more or less comparatively disappointing. Where selection is possible it will be conducive to best results on any plant to select those ores of the highest degree of purity by analysis that are available. The substitution of inferior ores almost invariably tends to increase the fuel used per ton of pig, with the attendant disadvantages. The selection of ores by analysis thus has an important bearing on furnace operation. To mention one point only, the iron content of the burden decides the amount of material it is necessary to pass through the furnace to produce 1 ton of iron, and, obviously, for output the less there is the better. Any increase of fuel means a larger *pro rata* volume of air to be blown for each ton of output, and there is a reflex action on the power of the blowing engines, number of stoves necessary, size of hearth for given output, and other important items.

Thus, with inferior ores the difficulties adversely affecting large outputs and low fuel consumptions increase and become cumulative, and possibly where modern blast-furnace plant is installed the disproportion between the relative value of high yielding and low yielding iron ores is increased.

Another point of importance in this connection is the necessity for a definite degree of uniformity, within fairly narrow limits, in the quality of ore, coke, and limestone.

Although it is, of course, true that, where fuel consumption per ton of pig iron is high, most of the potential value of the excess used still exists in the furnace gases and can be realised by fully utilising them, this is only a partial saving clause, and does not remove the drawbacks already mentioned.

Whilst published blast-furnace returns show that high yielding ores do not invariably give the best results, nor low yielding ores the worst, and also having due regard to the importance of

commercial and local considerations, in general the evidence distinctly shows that the quality of material used as determined by analysis is a factor of primary importance in its influence upon blast-furnace operation and results.

The selection of limestone is usually a commercial question, though obviously the purer the stone the more economical is its use in the furnace.

PREPARATION OF MATERIALS.

The great importance of preparing ores, and limestone or other fluxing agents, by bringing them to more uniform sizes than those in which they are mined or quarried (1 to 4 in. for ores, and 4 to 6 in. for flux) by crushing the lumps and by sintering or briquetting the fines, in order to increase and render more uniform the possible rate of reduction, and to ensure greater uniformity in their distribution in the furnace throat, has been emphasised in published papers, in experimental investigation, and in actual practice; but the Committee wishes to emphasise further the vital importance of this practice. Its beneficial effect upon regularity of operation, fuel economy and output is unquestionable, and in modern practice for large economical outputs it is an essential feature.

The detrimental effect of an excessive proportion of fine ore in an ore mixture upon furnace operation is well known. While modern design and practice have considerably reduced the difficulty of smelting fine ores, the excessive losses from flue-dust still remain an important factor in connection with their use.

The very considerable losses of ore in the form of flue-dust, which are practically unavoidable in the fast-driven modern blast-furnace plant when the ore mixture contains any material proportion of fine ore, has led to the adoption of methods of recovery by treating the dust to convert it into a physical condition suitable for recharging into the furnace. Many attempts have been made, previously, to recharge the coarser dust after wetting, but the results of this practice have generally been unsatisfactory.

Of recent years, in modern practice, the satisfactory recovery of this material has been attained by converting it into sinter by one or other of the well-known sintering processes, either alone

or after mixing with other fine ores. This practice is now considered "standard" in Germany and the United States.

An economic feature of this practice is the fact that flue-dust usually contains sufficient coke dust to permit of sintering without adding fuel, the amount of the latter being frequently sufficient to provide fuel, not only for the ore in the dust, but for a proportion of added ore as well.

(In Germany, blowing flue-dust into the furnace through holes in the upper stack, as a method of charging it without danger of its being redischarged into the gas flues, is practised in at least one locality, with claimed success; but no information is available as to the economic value of this practice as compared to recovery by sintering. It may be said that this method has the disadvantage of forcing the fine coke in the dust into the furnace as well as the iron-bearing dust, whereas this coke dust would doubtless have a much greater value as fuel in the sintering process.)

The principles upon which the importance of the preparation of ores and limestone, above outlined, is based, apply also to the fuel (coke) used in the blast-furnace.

Coke of large size presents a comparatively smaller surface area to the free action of the oxidising gases, and has a relatively retarding effect upon the total time for complete gasification. Also, the wider the difference between the size of the smaller and the larger lumps the less uniform the mechanical distribution, and the reactions, in the furnace.

While definite practice in the sizing of coke cannot be said to have become general in modern practice, there is a tendency in this direction, and very large coke is generally deprecated, and, where possible, avoided. Where applied, this practice has proved of advantage in its tendency toward greater regularity in furnace operation; in fact, at one plant in Germany the coke is crushed to $2\frac{3}{8}$ in., sizes under $1\frac{1}{2}$ in. being screened out, with such good results that other plants are also adopting this practice; and a furnace in the United States is working satisfactorily on crushed coke, a screen test of which as loaded into the skip tubs at the furnace is stated to be as follows:

On 2 in.	%
„ $1\frac{1}{2}$ in.	17.90
„ 1 in.	41.78
„ $\frac{3}{4}$ in.	27.80
Through 1 in.	12.52

On the other hand, small coke, up to the size of breeze, is generally considered objectionable for reasons similar to those applying to fine ores, and owing to its inefficiency as a blast-furnace fuel. Therefore, the practice of passing the coke over screens to remove the breeze, up to about 1 in. and even $1\frac{1}{2}$ in. in size, when a good market exists for small coke, has been found highly economical and has become quite general in modern practice.

The screening is done over fixed, or, preferably, moving screens as the coke passes from the coke bunker into the charging skip or bucket, the screenings being mechanically loaded into railway wagons. They are used for steam-raising at boilers, as fuel for ore sintering, or for any other purpose for which they are suitable.

Screening out the fines from ores containing any considerable proportion of them, when passing through the crushing plant, or from ores not requiring crushing, and treating them by the well-known sintering or briquetting methods, is an effective means of removing the objectionable features of smelting fine ores in the blast-furnace, and is a continually increasing factor in the preparation of materials.

The output capacity of blast-furnaces supplied with raw materials properly sized according to their density, including the elimination from the mixture of practically all "fines" by the use of the methods above mentioned, is materially increased per square foot of hearth area, with improved fuel economy—*i.e.* with furnaces of moderate hearth diameters and total volume charged with materials so prepared, the output capacities are equal to furnaces with considerably greater hearth diameters and volumes operated with materials not so prepared, and with reduced production and construction costs in economic excess over the cost of such preparation of materials.

Such results are entirely consistent with the greater regularity of operation (more uniform action throughout every cross-section of the furnace), and with the reduction to a minimum of the "flue-dust" losses.

The physical characteristics of the ores to be crushed must be taken into consideration in determining the method of crushing most suitable in each case.

With ores of a friable nature, in the crushing of which there

is a tendency to produce "fines," progressive crushing, as with the Blake jaw, Gates rotary, or revolving disc types, is not suitable, and the high-speed rolls type is indicated. With the latter the crushing operation is practically instantaneous, and repeated abrasion between the pieces of ore is reduced to a minimum. The latter type is also more suitable for ores having the slightest tendency to agglomerate under pressure.

Practically all of the usual methods which have been developed for rock-crushing are applicable to iron ores.

The type and layout of plant suitable for any particular case are determinable by local conditions, as no definite type or layout is especially suitable for iron ores.

With ores containing fines and rubble, screens for separating the lumps which need crushing should be provided, and where further treatment of the fines is advisable, screens should be provided for separating them from the rubble. Owing to the heavy duty, all plant must be of very substantial construction to ensure durability and efficiency; and capacity should include a considerable margin above the normally required output.

MECHANICAL HANDLING OF MATERIALS.

High wages for manual labour, together with the large quantities of raw materials required per unit of time with modern plant and practice, have necessitated the installation of mechanical means of handling these materials and the products. The old policy of "the smallest capital outlay per ton of product" has given place to "the greatest output per man employed." The latter policy can only be carried out by the installation of mechanical appliances. In modern plant manual labour is almost restricted to the manipulation of levers, thus replacing large numbers of men specialising in physique without the necessity for intelligence by a few men of intelligence without the necessity for physique.

The general features of a mechanically operated blast-furnace plant are too well known to require description, and the details of specific designs are too varied for inclusion in this Report, different types being fairly well standardised and each having its advocates. Suffice it to say that under existing severe economic competition

mechanical handling in practically every branch of blast-furnace operation is essential in modern practice.

This factor has reached, in some recent equipment, what may be considered practically the limit in labour economy, insomuch that one man only is required to control and carry on the entire charging of large capacity blast-furnaces. Each cycle of operations is started and carried out to completion in proper sequence automatically by a system of electric controls set into operation by the throwing of a single switch by the operator, without further attention. Overlapping through error on the part of the single operator is safeguarded by interlocking devices.

Of further economic importance is the mechanical handling of raw materials from mines or quarries, the delivery into railway wagons and into ships at loading ports, and the discharge from ships into railway wagons at receiving ports, or into stock at works, of sea-borne materials.

Facilities for these purposes include storage bunkers at the mines and shipping ports, from which the materials are discharged by gravity direct into self-discharging railway wagons of large capacity and/or into specially designed ships, the decks of which consist almost entirely of hatches, for rapid and complete unloading by means of large-capacity grab unloaders, such as the well-known Hulett or other types.

By these means very considerable economies are effected in loading, unloading, deck dues, and demurrage charges, and also in the time-service capacity of transport vehicles, both wagons and ships.

So many and varied, in both general arrangements and details, are the methods employed, and so varied are the opinions respecting them, that no particular method may be singled out as warranting special recommendation as the most efficient or economical.

FURNACE CHARGING AND TOP DISTRIBUTION.

In modern mechanically operated blast-furnace plants, charging and top-distributing devices are distinguished by two types in general, each characteristic in its method of dealing with the materials. Under these headings are the inclined and

the vertical-horizontal hoisting bucket-charging system, and the inclined hoisting skip-charging system.

Each of these systems provides for the equal distribution of the materials around the main charging bell; the former by a central discharge over the bell from the bottom of the bucket, and the latter by charging, by means of a tilting skip, through a preliminary distributing small bell and hopper equipment, which is automatically revolved through any selected arc after each skip-load is tipped into it, thus assuring equal distribution around the main charging bell.

On the Continent the former has been the most generally adopted type, while in the United States the latter is more generally used. The former may be designated as the method for handling large quantities slowly, and the latter as the method for handling small quantities quickly. Each is effective, and each has its advocates who claim the superiority of the one over the other in specific respects. Some such device, however, is a necessary accompaniment of modern mechanically operated blast-furnace plant. Many other arrangements have been brought out for assuring equality of distribution on the large charging bell, but the two systems above mentioned have become practically standardised.

In modern blast-furnace practice, too great emphasis cannot be laid upon the importance of the distribution of the raw materials within the furnace top. The wider the variation in the sizes of the components of any particular raw material, the less the uniformity of distribution of that material, and *vice versa*. Hence the importance, from this standpoint alone, of the preparation of the materials referred to.

The prevailing practice in charging the ore burden, when coarse and fine ores are in use, is to mix a proportion of each grade in each charge in order that the charges may be as uniform in mechanical characteristics as possible; but there have been recently published some very interesting results from a furnace in the United States, using a very dense ore crushed to $1\frac{1}{2}$ in. and under and screened into three sizes, designated as "coarse, medium, and fine."

By charging the three sizes in layers, each charge consisting of one size only, very considerable improvement in fuel consumption

and in other operating conditions were obtained compared with the results from the previous practice of crushing to 3 in. and under and screening into two sizes—*viz.* over and under $\frac{3}{4}$ in.

While it is quite possible that the characteristics of the ore in this case, particularly its density, may have a definite bearing upon the improved results obtained through the change in practice adopted, it cannot fail to have a very strong significance as evidence on the general question of the preparation of materials for blast-furnace use.

Great importance is attached to the angular discharge from, and to the diameter of, the main charging bell, in relation to the furnace throat diameter, the difference between these respective diameters being usually about 4 ft., with some degree of variation according to the mechanical condition of the ore mixture.

A further important factor in distribution is the size of the coke unit per round of charge. The tendency in modern practice has been towards an increase in this unit, one of the objects being to keep ore and coke as much as possible out of direct contact in the upper reducing zone, in order to restrict to a minimum the direct reduction of iron oxide by solid carbon in that region. Units as large as 6 and 7 tons have been used with satisfactory results in furnaces with moderate throat diameters.

FURNACE LINES (INTERIOR).

Developments in blast-furnace practice as regards interior design, or lines, have been the outcome of efforts towards an improvement in operating regularity and increase in output per furnace consistent with quality and economy. Efforts towards the attainment of these objects at first took the direction of great height and large interior volume, but the results of this line of development did not prove satisfactory. Following this phase, development took a direction which led to what may now be designated modern design; the distinctive characteristics, as compared with those of less modern design, are the larger hearth diameters, the low bosh, and the narrower shafts, the hearth diameter controlling, within fairly narrow limits, the other dimensions.

The latest developments in blast-furnace interior lines are

towards still larger hearth diameters and relatively smaller bosh and throat diameters. There are furnaces now in operation in the United States having hearth diameters of 24 ft. 0 in., 24 ft. 6 in., and 27 ft. 0 in., bosh diameters of 27 ft. 6 in., 26 ft. 3 in., and 28 ft. 6 in., and throat diameters of 18 ft., 17 ft., and 18 ft., respectively ; it is understood that the dimensions of the latter will be repeated in the next relining, which would seem to indicate that the results from this "super-furnace" have been entirely satisfactory. It is, therefore, questionable whether the limits in size and output have yet been reached with the now established monthly record of over 1000 tons per day, and what will be the factor establishing that limit when it is reached.

A limiting factor to much further expansion in this direction appears, however, in a relative increase in throat diameter, and in consequent bell diameter, in its bearing upon top distribution.

This limitation, on the other hand, may be overcome by a more uniform sizing of materials, as the less the difference in size between the smallest and the largest particles in the charge, the less important is the question of top distribution ; and the undesirable increase, through the use of larger bells, in the difference between the height of the stock column near the walls and the centre may be overcome by some improved method of distribution in the furnace top.

HOT-BLAST STOVES.

Cleaned gas having become standard practice, the modern hot-blast stove is designed with small checker openings, and in overall dimensions has become fairly well standardised with a comparatively small diameter, 18 ft. to 22 ft., and increased height, 90 ft. to 110 ft. Owing to the higher blast pressures, much stronger shell construction is required than formerly. In internal design the two-pass Cowper type has practically displaced other alternative types ; but a departure from the usual arrangement (internal combustion chamber) has been made in some stove installations with outside combustion chambers, which, it is claimed, give better distribution of air and gas, and eliminate the stresses on the brickwork.

Interior construction, including checker bearers and supporting columns, is wholly of firebrick, though a recent return to the use of castings in the bottom construction instead of brick piers, arches and transverse tiles is reported, the castings being, however, of a special heat- and oxidation-resisting quality. Checker openings are $3\frac{1}{2}$ in. to 5 in. sq., 4 in. to $4\frac{1}{2}$ in. sq. being representative of general practice with bricks $2\frac{1}{2}$ to 3 in. in thickness.

Efforts to improve checker construction are indicated by new designs brought out now and then, among which may be mentioned two cases of recent installation : one has round and square checker openings of $4\frac{3}{4}$ in. with $2\frac{3}{8}$ -in. to $1\frac{1}{16}$ -in. diagonal inserts put into the checker openings, thus increasing the heating surface ; the other has blocks perforated by 7 holes 1.89 in. in diam., or 19 holes 1.77 in. in diam. In some cases the upper halves of old stoves have been relined, with advantage, with the latter types of blocks. Higher efficiencies with lower stack temperatures are claimed for these constructions.

Shaped checker bricks are much less generally used than formerly, ordinary 9-in. bricks being largely used in checker construction, though there has been some return to the former.

In this connection, however, may be mentioned a recently introduced system of construction in the checker section of hot-blast stoves, by the use of which definite checker flues are replaced, or partly replaced, by short spiral-shaped bricks.

Stoves of this construction, in use at the Ilsede Ironworks, Gross-Ilsede, Germany, are reported to give results very superior to those from stoves of the usual checker flue construction.

Recent progress with hot-blast stoves is more particularly in the direction of improvements in gas-burner design for economy in combustion. A number of new designs of gas burners have been brought out during late years, chief among which are the pressure burners with automatic control of the gas and air mixture, the unit system of fans for air supply being preferred. Some systems embodying this type are the Steinbart system in the United States, and the Weyman system, of British origin. In Germany the P.S.S. (Pfoser-Strack-Stumm) system of gas burning in hot-blast stoves, in which the air is delivered at high velocity into the gas stream, is also growing in favour.

By these improved methods it is claimed that, due to the much higher efficiency obtained, fewer stoves or less total heating surface per furnace are required. This may be considered one of the principal objects to be attained through increased efficiency in stove gas combustion, another being of course the saving of gas for other purposes.

Greater attention is also being paid to the insulation between the stove linings and shell by means of special insulating material.

In hot-blast, cold-blast, and chimney valves, more or less standard designs prevail. For the first-named, the gate and the mushroom types are used, with water-cooled seats and valves of phosphor-bronze and cast-steel bodies. In cold-blast valves, the sluice-valve type of gate valve, vertical or horizontal, with cast-steel bodies and operated by rack and pinion, is most usual. In chimney valves the spectacle type is much used, though the removable type, similar to the pull-back gas valve arrangement, is also favoured. Recently a new type, similar in design to the flap check valve, has been brought out.

The adoption of two outlets for the waste gases from the stoves, for the purpose of improving the distribution of the gases through the checkers, is a feature in stove construction which, while not new, is increasing in use. Distant and automatic control of stove changing is a recent innovation in stove operation.

There has been no radical or recent alteration in general practice in these respects, though there are variations in the details in different designs.

GAS CLEANING.

Three distinct systems for gas cleaning are now in vogue :

- (1) Dry filtration—represented by the well-known Halberg-Beth type.
- (2) Water-spray washing—represented by the static spray washer, largely used, especially in the U.S.A., and the mechanical disintegrator or fan type, largely used, especially in Germany and in this country.

- (3) Electric deposition—represented by the Lodge and the Cottrell (now combined), and the Lurgi and the Elga.

The disposal of the dust in the form of sludge, and the pollution of the washing water with No. 2, are bothersome under some conditions. For the prevention of the deposition of fine wet sludge and water (carried over by the washed gases) into the gas mains, previously an objectionable feature, supplementary heating of the washed gases to a sufficient degree to vaporise the entrained moisture and dry the fine sludge, for which a temperature rise of 30° to 50° F. is claimed to be sufficient, has recently been introduced in the United States. The apparatus is a heat interchanger, constructed on the principle of the tubular boiler, the heating medium being the waste gases from the hot-blast stoves. The washed gas passes through the tubes and the waste gases through the body of the interchanger. Provision is made for periodic cleaning of the tubes in nests of a few tubes each without interruption of operations or material reduction in efficiency. This supplementary heating is said to have proved satisfactory and economical, in which case the static wet system of cleaning has the recommendation of simplicity and ease of operation. This system, except when supplemented by Theisen or other mechanical washers, is only suitable for cleaning gas for heating hot-blast stoves, boilers, and some other heating purposes—*i.e.* what is generally designated “rough cleaning.” There appears, however, to be a tendency, particularly with stoves having very small checker openings, towards secondary cleaning by disintegrating washers, or electric precipitation, indicating a growing recognition that a higher degree of gas cleanliness, in such cases, is necessary and more economical in gas consumption.

Preheating of air and gas, and also of blast, before they enter the stoves, by the utilisation of the heat in the waste gases from the stoves, or in the raw hot gases from the furnace, are steps towards further economy which have been reported in several installations. Increases of 270° F. in the blast temperature, and 90° F. in the gas temperature, before entering the stove, are said to have been obtained.

No. 1 system is suitable for cleaning gas to that high degree required for use in internal combustion engines.

GAS BURNING AND SURPLUS GAS.

Much attention has been given of late to efficiency and consequent economy in the combustion of blast-furnace gas in hot-blast stoves, boilers, &c. (to which reference has been made under hot-blast stoves), by systems of automatic regulation of the gas and air mixture, some of which are proving highly efficient in blast heating and power production, thus increasing considerably the quantity of surplus gas available for purposes other than the blast-furnace plant requirements, such as the generation of electric current for steelworks operation, and for sale to local communities and industries; for open-hearth and other heating purposes with or without the admixture of coke-oven gas when available; for coke-oven heating, thus setting free the richer coke-oven gas for other purposes as mentioned above, and for sale to gas companies for lighting and heating in neighbouring communities.

Valuable returns are thus obtained for credit to the pig iron production costs.

BLOWING PLANT.

In modern blast-furnace plant the blast-furnace gas-driven reciprocating engine and blower, and the steam turbine-driven turbo-blower, are the two types of blowers now almost universally installed.

The gas-driven blower, developed in Germany, has, until very recently, held the field in that country, while in the United States this type has been practically superseded by the turbo-blower. Recent information seems to indicate that the latter type is now making headway against the former on the Continent. This is doubtless due to its greater simplicity, lower first and operating cost, and the improved economy in high-pressure steam generation.

It is also probable that with the increased volume and pressure and capacities required for large modern blast-furnaces, which have risen to 60,000 cu. ft. and at some recent plants to 75,000 and 90,000 cu. ft. per min., and up to 30 lb. per sq. in., the single unit blower per furnace being preferred, units of such high power are more practical and economical in the turbo-blower type than in the gas-engine type.

POWER PLANT.

In more recent years the feature in new blast-furnace plant installations which has made the greatest advance is the production of power. Considerable economies in this direction have been effected by the use of boiler units of large capacity generating steam at high pressure, 300 lb. per sq. in. and upwards (in some cases electric generating stations using steam pressures as high as 600 lb. per sq. in. are in satisfactory operation), with blast-furnace gas burned in automatically controlled burners, and the unit system of powdered coal as alternative standby.

The conversion plant consists of high-pressure, superheated steam turbines for blowers and for electric generation at high voltage, the latter being transformed to whatever lower voltages are required for each class of power application.

Great attention is paid to the keeping of records in connection with each step in power production operations (for which the standards set for attainment are high) by means of appropriate instruments, for checking results. Boiler steam-flow meters, recording pyrometers, draught gauges, steam consumption meters, &c., give complete records of the conditions of power production and of the power consumption of the various using units.

Power-using items adjacent to the boiler plant are usually steam-turbine driven and others electrically driven. Boiler efficiencies up to 80 per cent. are stated to have thus been obtained.

DRY BLAST.

The economic advantages of dry blast in blast-furnace operation are generally accepted as material, but heretofore the high cost of plant for the extraction of the moisture in the blast has militated against progress in this direction.

The recently introduced method of drying atmospheric air by means of "silica gel," and the installation of such a plant at a Scottish works, has renewed interest in this economic feature. While it is, perhaps, too early to draw definite conclusions as to the efficiency of this device from the results thus far reported which have been very favourable, results over a longer period are awaited with great interest.¹

¹ (See E. H. Lewis' paper on "Twenty Months' Results of Dry Blast Operation," this volume, p. 79.)

PIG IRON CASTING.

With modern blast-furnace plant and practice, casting in sand-beds for most classes of pig iron is rapidly becoming obsolete ; in fact, with large modern outputs that method of dealing with the product is economically impracticable.

When combined with steel smelting, direct transfer of the molten metal in hot-metal ladle cars to smelting shop mixers has long been standard practice ; but a more recent development in this respect is the growing use of the totally enclosed, or mixer, type of ladle of comparatively large capacity (originally brought out for special long haulages) for the ordinary transfer of hot metal between blast-furnaces and smelting shop in the same works ; this type of ladle is more economical than the usual type of open-top ladle, notwithstanding its higher first cost, owing to its much greater conservation of the heat in the hot metal, the saving in skull formation and in relining repairs. For week-end metal, when not taken by the smelting-shop mixers, and for emergencies when metal is not required there, pig-casting machines are the usual installation when warranted by the tonnage.

At blast-furnace plants not combined with smelting works machine-casting is becoming standard practice, and this method is now much used even for foundry iron, though machine sand-moulding is making some headway. While there is still some controversy as to whether machine-cast foundry iron is as good as that cast in sand, many foundries are using the former with entire satisfaction.

The Uehling type of pig-casting machine, with an endless chain of moulds, with or without a water trough for cooling the iron, is the type now most generally used.

GENERAL LAYOUT OF PLANT.

No definite layout arrangement can be said to be distinctive of modern blast-furnace plant, as each arrangement of the various sections comprising such a plant is dependent upon local circumstances, the shape of the space available, the ideas of the designing engineer, &c. Where, however, ample space is available, what

may be designated as the straight-line layout is probably representative of most modern plants. This layout is designed primarily for straight-through railway lines in touch with practically every part of the plant from either end, "dead-end" branch roads being entirely eliminated or reduced to a minimum. The plant may be said to be divided into "lines" comprising :

The power production and power conversion section.

The furnace, hot-blast stove, and gas-cleaning section.

The raw material storage bunker and charging equipment section.

The raw material storage ground and bunker charging equipment section.

The raw material receiving equipment section.

Between the sections run one, two, or more through railway lines, with crossovers, which serve the various portions of the plant, and where necessary short branches from the through roads serve specific points.

When a plant consists of two or more furnaces (multiples of two) each pair may form a two-furnace unit. The hot-blast stoves for each pair are placed between and in line with the two blast-furnaces, or else the furnaces may be placed side by side in the middle, with the stoves in line outside.

All through railroads eventually join into two or more main roads beyond each end of the plant, thus providing access to any part of the plant from either end, the main roads being also connected by a road, or roads, running along the outside of the whole plant. In the layout of the railways consideration must be given to suitable locations for weigh-bridges, so that all incoming and outgoing materials may be accurately weighed without danger of congestion.

Compactness and railway accessibility, without congestion, are the principles aimed at ; the former provides for convenience of supervision, and the latter for ease and economy in distribution of raw materials and the disposal of products and waste materials.

Offices, laboratories, shops, &c., are placed in the open spaces between the converging roads beyond the plant proper, as such space permits, or at any other convenient points.

USE OF RECORDING INSTRUMENTS IN CONNECTION WITH THE OPERATION OF THE BLAST-FURNACE.

In view of the great increase in the outputs of modern blast-furnaces it becomes imperative that the various operations be very carefully supervised, and that as far as is possible such supervision should be centralised. As it is humanly impossible for one person to keep in contact with all operations at all times, modern works have been equipped with a large number of automatic measuring instruments, mostly of the recording type, and generally assembled in one room. One or more assistants are set to watch the variations shown by the different instruments. The moment anything abnormal is noticed, the man for the time being in charge of the blast-furnaces is notified as soon as possible, so that he can investigate the cause of the disturbance and take steps at once to put it right.

The items generally indicated or recorded in the instrument room are the following :

- (1) Height of stock line in the furnace and number of charges.
- (2) Temperature and pressure of gas at top of furnace.
- (3) Number of revolutions of blowing engines or volume of blast blown.
- (4) Pressure of blast before entering stoves and pressure in the circular main.
- (5) Temperature of blast in circular main.
- (6) Temperature of blast at stove outlet (as a check for that in the circular main).
- (7) Temperature of flue gases at chimney valves of stoves.
- (8) CO_2 contents of flue gases at chimney valves of stoves.
- (9) Pressure of gas in main.
- (10) Volume of gas going to stoves (in group).
- (11) Volume of gas going to power-house.
- (12) Pressure of gas before entering gas-cleaning plant and pressure when leaving.
- (13) Volume of gas stored in holder.
- (14) Steam pressure and volume of water evaporated, if blowing and power plants are steam-driven.
- (15) Bus-bar voltage at generating station.

An attempt is being made in Germany to do all the changing of stoves—*i.e.* operation of all valves—from the instrument room by either electric or hydraulic power. In a good many plants the gas and air supplies to stoves are regulated automatically, and in at least one works the analysis of the top gases is made automatically, and the different percentages of their constituents are shown on the instrument board.¹

Such a system naturally requires a great number of reliable instruments. A numerous staff with special knowledge of the instruments in use is detailed to check their accuracy and to repair those which show defects.

OXYGEN ENRICHMENT OF BLAST.

Much thought has been given to this subject in past years, and at least one practical application was made on a commercial scale to a blast-furnace at Liège, in Belgium.

It is stated that very small additions of oxygen were sufficient to overcome the detrimental effects of the atmospheric moisture in the blast; and that enrichment up to 25 per cent. of oxygen made it possible to dispense with hot-blast stoves, and produced a higher grade of iron. No information, however, appears available as to the commercial results of this trial.

A recent investigation into this subject is embodied in a report by a committee formed under the auspices of the United States Bureau of Mines, on the "Use of Oxygen or Oxygenated Air in Metallurgy and Allied Processes."²

A symposium on the "Use of Oxygenated Air in Metallurgical Operations" was held at the New York meeting (February 1924) of the American Institute of Mining and Metallurgical Engineers; abstracts from the papers forming the symposium, including a summary of the report of the Bureau of Mines Committee, have been published by the American Institute of Mining and Metallurgical Engineers.³

The following quotation from the "Foreword" of this

¹ H. Bansen, *Archiv für das Eisenhüttenwesen*, 1927, vol. i., Oct., pp. 245-266.

² F. Davis, *U.S. Bureau of Mines*, 1923, *Report of Investigations*, No. 2502.

³ Pamphlet No. 1377-8.

pamphlet gives the gist of the result of the discussion at the symposium :

“An extensive discussion followed the presentation of the papers, which dealt with the matter entirely from a theoretical standpoint. The results of only a limited amount of research work were presented. . . . More experimental work on this subject has not been done because metallurgists have not thought that cheap oxygen could be produced, thinking, ‘Why waste time experimenting with a reagent that cannot be procurable in commercial quantities?’; while the producers of oxygen have said, ‘Why waste money on the development of a process to make cheap oxygen unless we know that there will be a market for it when produced?’

“The discussion brought out two facts: First, many metallurgists believe that their operations can be conducted more economically if they can add oxygen to the air used in various smelting operations; second, a number of chemists believe that relatively pure oxygen can be produced in metallurgical quantities at very small cost. Negative views were expressed to both propositions, but so overwhelming was the view that if cheap oxygen could be produced many metallurgical operations would benefit, that it was voted to recommend that the Bureau of Mines continue its research work, pending the production of the cheap oxygen hoped for.

“Few experimental data being available, and the attitude of disputants being based largely on theoretical considerations or on reactions and temperatures incapable of positive proof, it has been decided to publish only a summary of the papers and discussions arising from their presentations. It is believed, however, that this will be sufficient to show the lines of reasoning that have been adopted, and be a guide to others who are to make their own calculations or engage in experimental work.”

It appears that no definite conclusions were arrived at by the Committee or from the discussions, except that the Bureau of Mines should continue its research work, and that a process for the production of cheap oxygen should be sought.

This subject, therefore, offers two fields for research, the commercial value of each being dependent upon the other; and the degree of progress in these fields is the factor governing further practical application on a commercial scale.

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DISCUSSION.

Mr. A. HUTCHINSON (Vice-President) said the members were greatly indebted to the Blast-Furnace Committee for giving such a complete review of the advances made in blast-furnace practice in recent years. Whereas there might be nothing particularly new in it which could not be gleaned from the journals published in the different countries, it was very useful to have the information focused in the way in which it had been in the Report, and the Blast-Furnace Committee had done extremely valuable work in that respect. One of the outstanding features of modern practice was the large and continuously increasing hearths in the big American furnaces; one began to wonder how much further their size would be carried. It was indeed interesting to read that the latest furnace with the very largest hearth capacity was so successful that further furnaces of that type would be built. Even with 1000 tons a day the limit seemed not to have been reached.

Professor T. TURNER (Member of Council) remarked that he had not been very closely interested in blast-furnace work during the last few years, but he realised the value of the contribution received from the Blast-Furnace Committee. The last speaker had referred to the size of furnace hearths, and the President had dealt with the history of iron. He might be permitted, therefore, to mention one matter in connection with the history of blast-furnace hearths. It was just about one hundred years ago that the old square blast-furnace hearths were replaced by round hearths. It had been noted that the hearths when first put in had given a smaller yield of iron than when they had been working for a few weeks or months. Oakes, of Dudley, took the rash step of building a furnace with a new form of hearth; he thought it would be better to start straight away with the form of hearth which it had been observed gave the best results, namely, the round hearth. Oakes was only a young man at that time, and he (Professor Turner) had had the opportunity, about 40 years ago, of discussing with him those early experiments. So that it was only a matter of one hundred years just two lifetimes—to go back from the present wide hearths to the small square hearth, a little more than 2 ft. in size, which had then been the practice of the country.

Professor C. H. DESCH, F.R.S. (Member of Council), said he had been struck when visiting American works by the great importance attached to the grading and sizing of the coke. The coke that he had seen in Pittsburg furnaces was very inferior to English blast-furnace coke in quality, and, after manufacture, it easily broke up into pieces mostly about $2\frac{1}{2}$ in. cube or so; but everything below $1\frac{1}{2}$ in. was screened out. He had found that the large outputs of certain furnaces were attributed by the managers to a great extent to that careful grading of the fuel.

The Blast-Furnace Coke Committee which sat at Sheffield had had that question under consideration several times, and he thought it was one of the most important points referred to in the Report of the present Committee.

Mr. F. W. HARBORD, C.B.E. (Past-President), wished to join with other speakers in congratulating the Committee on having given so excellent a summary of blast-furnace conditions at the present time. The object of such technical committees was to place before the members in an accessible form all the latest developments in the particular branches of the industry with which they dealt. The Report gave a very clear and concise account of the latest developments in blast-furnace practice on the Continent, in America, and in this country. It also pointed, in a very clear way, to those developments which, in the opinion of the Committee, were of special interest and likely to lead to the most important results, and to which, therefore, iron-masters and managers should give special attention. He hoped that one of the things referred to by the Committee would be carried out—namely, that in the event of any new development taking place which, in the opinion of the Committee, justified further investigation, arrangements would be made for experts to investigate the matter and report to the Institute. In that way the members would be kept in the closest touch with the developments of their industry.

Mr. E. C. EVANS (London) referred to one paragraph in the Report in which it was suggested that a 1 per cent. decrease in the ash was equal to a 2 per cent. increase in the value of the coke. The point was important, because one of the Coke Research Committees was considering what value should be allowed for decreasing ash content in coke. If coke were taken at 17s. 6d. a ton, a decrease of 1 per cent. of ash would, in accordance with the calculation referred to, increase the value of that coke by 4d. a ton. It had been shown by Mr. Gill at Consett, and by other observers, that a 1 per cent. decrease in ash would decrease the fuel consumption per ton of pig by something of the order of 0·4 cwt., which would be worth about 4d. per ton. That, however, took no account of the increase in output, saving in limestone, and other factors which were important from a practical costing standpoint; and as iron and steel works in many cases sold as well as purchased coke, he thought that the fullest value should be allowed for a decrease in the ash content.

Sir FREDERICK MILLS, Bt. (Past-President), congratulated the Committee on the work they had done, and also the Institute on setting up such committees. He thought they were long overdue; in fact, there was a hiatus of nearly half a century between the work which had been done by Sir Lothian Bell and the work which was now being done by the present Committee. It was surely very much better for a group of scientists to tell the industry what to do than to leave it to the

industry to find out by rule of thumb. He had been very much struck by some of the results which had been given and even more so by the explanations which were given for those results. He would like it very much if the scientists would state the reasons for some of the things which had been found in practice. For instance, the application of the turbo-blower had almost completely done away with scaffolding in blast-furnaces; was there any really satisfactory scientific reason for that? Nothing very much had been said, during the present discussion at all events, on the subject of the effect of excessive moisture in coke. He was not at all sure that good working was not almost entirely a matter of regularity in the content of moisture. Everyone who had to consider day-to-day figures got, under equal conditions, variations equal to the amount of saving which were described by Mr. Lewis¹; and, after further investigation, an explanation might be obtained from blast-furnace managers of a more scientific character than those usually given—which were generally excuses rather than reasons. In short, he welcomed very much the departure from the rule-of-thumb methods; he hoped the investigations would be continued, and, moreover, kept up as a permanent means of ascertaining and recording the causes for the variations which were obtained in actual practice.

Mr. T. H. TURNER (Birmingham) referred to the passage stating that machine pig casting had become the standard practice even for foundry iron, and said that hardly seemed true for Great Britain. Observations of the stocks of the Midland foundries did not appear to confirm that statement. A few years ago Great Britain seemed to be losing a market for pig iron on the eastern coast of the United States. It was then stated that the people in that market would be quite willing to buy British pig iron if only it were sent out in the form of machine-cast uniform-sized pig. The foundries which he (Mr. Turner) visited at that time had actually had pigs from different European countries, and those in charge pointed out to him the great difference in shape and size between the pigs and sows, and the uniform suitable dimensions of the American machine-cast pig iron.

The Report as a whole followed very closely on the lines of Mr. Reese's paper of September 1922,² and he would like to say that, to those whose duty it was to advise reading for students, papers of that type were invaluable.

Mr. A. K. REESE, replying on behalf of the Blast-Furnace Committee, thanked the various speakers for their remarks. He hoped the Report would be of benefit to those who were sufficiently interested to follow up the various innovations mentioned in it. At the end of the Report was a long list of references which might be consulted, and

¹ See E. H. Lewis' paper, this volume, p. 79.

² *Journal of the Iron and Steel Institute*, 1922, No. II. p. 9.

in which details of many of the matters referred to in the Report would be found.

With regard to the question which Mr. T. H. Turner had raised, it was a fact that in the United States foundrymen had been educated up to the use of machine-cast pig, and, while there were still some who grumbled at it, the vast majority of foundrymen were glad to have their iron in that form. He thought the same thing would apply in Great Britain if the makers of pig iron set to work to educate the foundrymen to the use of machine iron. As a matter of fact, in this country there were many small and independent furnaces making pig iron, practically none of which had adopted the machine-cast method. They really did not need it, because their outputs were not large enough to warrant an outlay for a casting machine. It would therefore be a very difficult matter for those who had installed casting machines to insist on the foundrymen taking machine-cast iron, because they (the latter) could easily get sand-cast pig. The casting machine in Great Britain was more adaptable to the steel-making works for taking care of the surplus week-end iron or other surplus pig iron from the blast-furnace. But when the day came when the foundry iron would also be produced in large units—too large for sand-casting—then it would only be a question of educating the foundrymen to use it; they would find they could use it, and could make just as good castings with machine-cast iron as they did now with very "special" brands of sand-cast iron.

Referring to the question of scaffolding, it was very probable that the difference which Sir Frederick Mills had noticed in the scaffolding of his furnaces since the introduction of the turbine was due to the alteration in the lines of the furnaces which had accompanied the growing use of the turbo-blower. He thought, in a general way, Sir Frederick would find that the narrow bosh and low bosh and the steep angle had grown up and had been more generally used at just about the same rate at which the turbo-blower had been coming into general favour, and he thought it likely that the improvement in results in Sir Frederick's furnaces, in the respect he had mentioned, was due to better lines of the furnace rather than to the actual use of the turbo-blower. At the same time, there was no doubt that the turbo-blower did give a more steady flow of air. Whether that had any effect on the scaffolding tendencies of the furnace or not he could not say.

Mr. Evans had said something about the question of saving due to the reduction of ash in coke—a matter which was mentioned in the Report. He had no figures with which to answer the question, but in principle considerable saving was quite evident. If one changed from a coke containing 10 per cent. of ash to one containing 13 per cent. of ash, the slag volume would be increased, which would take more coke to melt it, and the percentage of carbon in the coke would be reduced, which reduced its efficiency. Those two points alone were sufficient to indicate that there was an advantage in low-ash over high-ash coke, presuming that the ores were not so free from silica that some silica had to be put into the furnace in order to make enough

slag. He would ask Mr. Wright, a member of the Committee, to say a word on the subject.

Mr. H. E. WRIGHT replied to Mr. Evans' question that it was found that 1 per cent. of ash replaced 1 per cent. of carbon in the coke. In addition to that, the 1 per cent. of ash formed blast-furnace slag—that was to say, it formed the portion of blast-furnace slag which had to be fluxed largely with limestone. In Mr. Evans' paper¹ the comparison of figures for furnaces giving a yield below 2000 lb. of slag per ton of iron and those above 2000 lb. of slag per ton of iron showed that the coke consumption with the higher amount of slag ran out at exactly 0·6 lb. of coke per lb. of extra slag. Taking ash as a proportion of the slag, and adding lime to it, it made it grow 12 times as much. Mr. Evans' records of 116 English furnaces, and also American furnaces, showed that 2000 lb. of slag required 0·63 lb. of carbon per lb. Adding two-thirds of that would give the exact figure—two of carbon to one of ash. Of course, it might be more, but the Committee would dispute it being less. They would dispute that ash could be dealt with by less than the absorption of 1 per cent. of carbon which it replaced and 1 per cent. of carbon to smelt it. It might take more. If that was Mr. Evans' argument, the Committee would not dispute it.

This Report was also presented at the Additional Meeting held at Glasgow on May 9, 1929.

The CHAIRMAN (Mr. R. Hamilton) remarked that the names of the members of the Committee who had prepared the Report were a guarantee that it was an authoritative statement of the condition of blast-furnace practice and of the plant that was being used. On p. 50 there was a statement that an increase of 1 per cent. of ash, in round figures, was equal to a 2 per cent. decrease in the coke value, due to the necessity of melting the ash which had replaced 1 per cent. of carbon in the coke. He was not very clear about that, and, in trying to put it in concrete form, he took the price of coke to be 20s. per ton. Now, if the ash were increased by 1 per cent., that would be a 2 per cent. decrease in the coke value, and 2 per cent. of 20s. was about 5d.

In regard to the selection of ore by analysis, it was easy to speak of the amount of fuel required per ton of iron, but, while that was all right for one works using a certain class of material, for comparison with another works using different materials something more was required. He had an experience, during the war, of using ore of inferior quality, which gave more slag than iron. It was obviously unfair to compare the amount of fuel required to make a ton of iron when using materials of that nature with that required when using other and better ores. It was unquestionable that preparation of ores and limestone to a uniform size was beneficial.

¹ E. C. Evans and F. J. Bailey, *Journal of the Iron and Steel Institute*, 1928, No. I. p. 53.

TWENTY MONTHS' RESULTS OF DRY BLAST OPERATION.¹

By EDWIN H. LEWIS, M.A., F.INST.F. (WISHAW).

IN 1927 the author published the results of four months' work at the Wishaw blast-furnaces with air dried by means of a silica gel dehydration plant.² He is now able to give more complete figures for the twenty months during which the plant has been in operation. They are collected together in Table I., which, with some slight alteration, is set out in the same way as that containing the earlier results (*loc. cit.*, p. 49).

Moisture in Atmosphere.—The amount of moisture in the atmosphere in the "standard year" was previously given as 3·5 grains per cu. ft. This was the only figure then available, and was obtained from a station in the district. A comparison of subsequent records taken at Wishaw and at the same station showed that the Wishaw figure for 1925 should have been stated as 3·21 grains per cu. ft., and the table has been altered accordingly. The figures in Table II. show the maximum and minimum moistures observed for each month at Wishaw.

Silicon in Pig Iron.—Evans and Bailey have shown the importance of silicon content in connection with the consumption of carbon in the blast-furnace.³ The average figures for silicon have therefore been added to Table I. An analysis of the Wishaw results taken month by month, according to Evans and Bailey's equation³ (*loc. cit.*, p. 65),

$$C_1 + C_2 = \frac{500}{D} + [0\cdot4 + (0\cdot12 \times \% \text{ Si})] \times I + 0\cdot28S,$$

proves that equation to be substantially correct, except that for furnaces which are not water-cooled the radiation constant of 500 is too high. For a wide range of conditions and of qualities

¹ Received February 21, 1929.

² *Journal of the Iron and Steel Institute*, 1927, No. II. p. 43.

³ *Ibid.*, 1928, No. I. p. 53.

TABLE I.—*Twenty Months' Operating Results.*

	1925.	May 1927.	June 1927.	July 1927.	Aug. 1927.	Sept. 1927.	Oct. 1927.	Nov. 1927.	Dec. 1927.	Jan. 1928.	Feb. 1928.	Mar. 1928.	Apr. 1928.	May 1928.	June 1928.	July 1928.	Aug. 1928.	Sept. 1928.	Oct. 1928.	Nov. 1928.	Dec. 1928.	Jan. 1929.
Moisture in atmosphere. Grains per cu. ft.	3.21	3.08	3.41	4.85	4.77	4.08	3.53	2.84	2.21	2.47	2.46	2.43	2.63	2.99	3.17	3.91	4.19	3.64	3.33	2.88	2.38	3.26
Moisture in blast. Grains per cu. ft.	3.21	1.09	1.20	1.61	1.50	1.36	1.45	1.20	1.22	1.24	1.24	1.25	1.26	1.34	1.55	1.74	1.89	1.55	1.29	1.26	1.25	1.37
Output per furnace per week. Tons	356.5	418.5	400.0	417.6	412.9	404.5	399.2	405.2	410.0	391.3	424.9	407.5	409.2	406.3	364.2	392.3	372.2	399.9	411.2	426.0	385.2	403.8
Percentage increase in output	...	17.39	12.20	17.14	15.82	13.46	11.98	13.66	15.01	9.76	19.19	14.31	14.78	13.97	2.16	10.04	4.40	12.17	15.31	19.50	8.05	13.27
Total carbon per ton of iron. Lb.	2055	1961	1938	1956	1947	1920	1960	1983	1954	2030	1998	1939	1913	1901	1903	1814	1927	1929	1919	1922	1936	1943
Percentage saving in fuel	...	4.57	5.69	4.82	5.55	6.52	4.62	3.50	4.91	1.22	2.77	5.64	6.91	7.49	7.40	10.27	6.23	6.13	6.61	6.47	4.81	5.45
Carbon burnt at tuyeres per ton of iron. Lb.	1705	1811	1888	1606	1597	1570	1610	1633	1604	1680	1648	1589	1563	1551	1553	1494	1577	1579	1569	1572	1606	1593
Percentage saving in fuel burnt at tuyeres	...	5.51	6.86	5.81	6.33	7.92	5.57	4.22	5.92	1.47	3.34	6.80	8.33	9.03	8.91	12.38	7.51	7.39	7.98	7.80	5.81	6.57
Balance of available hearth heat per lb. of carbon burnt at tuyeres (according to Johnson). B.t.u.	1601	1724	1717	1694	1700	1708	1703	1717	1716	1715	1715	1714	1714	1709	1697	1686	1677	1697	1712	1713	1714	1708
Theoretical saving at carbon burnt at tuyeres (according to Johnson). Per cent.	...	7.13	6.76	5.49	5.82	6.26	5.99	6.76	6.70	6.65	6.65	6.59	6.59	6.32	5.66	5.04	4.53	5.66	6.48	6.54	6.59	6.26
Theoretical balance of available hearth heat per lb. of carbon burnt at tuyeres for actual atmospheric moisture for month	...	1609	1590	1509	1514	1552	1583	1622	1659	1644	1645	1646	1634	1614	1603	1562	1546	1578	1594	1620	1648	...
Theoretical saving in carbon burnt at tuyeres for actual monthly conditions. Per cent.	...	6.67	7.39	10.92	10.94	8.97	7.05	5.53	3.32	4.14	4.08	3.97	4.67	5.56	5.54	7.35	7.81	7.01	7.48	5.43	3.85	...
Average silicon in pig iron. Per cent.	2.90	2.55	2.73	2.62	2.68	2.57	2.61	2.57	2.48	2.57	2.42	2.37	2.22	2.22	2.52	2.49	2.84	2.99	3.09	2.52	2.55	2.56

¹ Furnaces on slack blast for part of month.

of iron this equation shows that for furnaces of the usual Scottish type the radiation constant should be about 350 on the yearly

TABLE II.—*Atmospheric Moisture.*

1927.	Moisture in Atmosphere. Grains per cu. ft.		1928.	Moisture in Atmosphere. Grains per cu. ft.	
	Maximum.	Minimum.		Maximum.	Minimum.
			January . . .	3.94	1.48
			February . . .	4.15	1.63
			March . . .	4.13	1.40
			April . . .	4.86	1.05
May . . .	5.88	1.47	May . . .	5.43	1.38
June . . .	5.57	1.33	June . . .	5.27	1.73
July . . .	6.51	3.62	July . . .	6.21	2.18
August . . .	6.56	3.26	August . . .	6.05	2.87
September . . .	6.88	2.36	September . . .	5.84	1.71
October . . .	5.73	1.71	October . . .	5.26	2.20
November . . .	5.62	1.38	November . . .	4.98	1.90
December . . .	3.81	1.22	December . . .	4.11	1.34

average, with slight variations between summer and winter, as shown in Table III. :

TABLE III.—*Monthly Average "Radiation Constants."*

Month.	Average "Radiation Constant" for Four Furnaces.	Month.	Average "Radiation Constant" for Four Furnaces.
January . . .	373	July . . .	330
February . . .	368	August . . .	346
March . . .	358	September . . .	353
April . . .	360	October . . .	316
May . . .	346	November . . .	342
June . . .	327	December . . .	355

The uniformity of these results with irons ranging from 1.26 to 3.74 per cent. of silicon points to the accuracy of the silicon coefficient of 0.12. If this coefficient be used and a blast temperature of 1450° F. (788° C.) be assumed, then the extra carbon (*C*) required per ton of iron for each 1 per cent. of silicon is found to be :

$$C(1 + 1450 \times 0.000317) = 0.12 \times 2240 \text{ lb.}$$

that is,

$$C = 184 \text{ lb.}$$

In Table I. the average silicon during the twenty months is given as 2.56 per cent. as against 2.90 per cent. in 1925, while the carbon consumption was 1943 lb. instead of 2055 lb. Of the total saving of 112 lb. of carbon per ton of iron, 0.34×184 , or 63 lb., is connected with the lower silicon content. It has been found very much easier to make lower silicon iron with dry blast; in fact, when good coal was available it was possible to make basic iron, with less than 1 per cent. of silicon and less than 0.06 per cent. of sulphur, with 90 per cent. of raw coal and a carbon consumption of 1622 lb. per ton of iron.

By-Product Recovery.—The recovery of creosote oil has increased by 0.718 gal. per ton of coal, due probably to the lower temperature of the top gases. The loss of ammonia mentioned in the author's previous paper has proved to be equivalent to 1.13 lb. of sulphate of ammonia per ton of coal.

Optimum Dryness.—On three different occasions the moisture in the blast has been below 1 grain per cu. ft., and each time the burden had to be decreased to avoid "cold" iron. It appears, therefore, that 1 to $1\frac{1}{2}$ grains per cu. ft. is the best amount of "dryness" at which to aim.

General.—Among other advantages of dry blast observed during the twenty months should be noticed the absence of "slips," the quick recovery of sticking furnaces, the improvement in quality of pitch due to the absence of slips, and the possibility of using a larger proportion of soft coal with a decreased proportion of coke.

The total quantity of water removed from the blast was 2373 tons, or 32 lb. per ton of iron.

DISCUSSION.

Mr. A. HUTCHINSON (Vice-President) desired to congratulate Mr. Lewis on the very excellent work which he had done. Most people recognised that in the Wishaw plant Mr. Lewis had had a special opportunity of carrying out the research and showing the effect of the new method of drying blast. It had proved most successful, and an economy such as had been described was one worth very careful consideration in any plant where similar conditions applied.

Professor C. H. DESCH, F.R.S. (Member of Council), asked Mr. Lewis for information as to the life of the silica gel. When the gel was kept quite free from poisoning presumably it would last indefinitely, but it must be difficult to keep out slight traces of tar; he would be glad if Mr. Lewis would say whether it had been necessary, and if so how often, to renew the charge of silica gel in the plant. Mr. Lewis' furnaces were slightly exceptional in that they were working largely with raw coal, and whether the same advantages could be got where typical blast-furnace coke was used, would be an interesting question to examine.

Mr. F. W. HARBORD, C.B.E. (Past-President), said he did not know why it should be assumed that similar good results should not be obtained in a modern furnace working with coke. It had been admitted by nearly all metallurgists that there were great advantages in having dry blast. Not only did one get decreased fuel consumption, but one got what was almost of greater importance—greater uniformity of product. It all came down to a question of cost. He believed the Gayley process had failed entirely on the question of capital cost. It would greatly add to the value of Mr. Lewis' paper if he could give some approximate figure as to the capital cost of the plant per 1000 cu. ft. of air passed through. Then ironmasters would be able to consider seriously how far that expenditure would be justified.

Mr. A. K. REESE (Weybridge) desired to refer to one matter mentioned by Mr. Lewis, and also to reply to Mr. Harbord's reference to the applicability of dry blast to coke furnaces. He had had the opportunity of working dry blast for many years on coke furnaces producing from 2000 to 2500 tons of pig iron per week, and the advantage over natural air operation had been most marked. He had submitted to the Institute, in previous discussions, figures comparing the results which had been obtained with those resulting from natural air operation. Very careful records had been made for several months immediately prior to, and for several months immediately after, the

application of dry air. Those figures showed that with the coke furnaces an even greater improvement was obtained from dry air than Mr. Lewis could get with his coal furnaces, though that might have been due to the larger furnaces and other local conditions.

Mr. Lewis had referred to the chilling effect on his furnaces of a reduction of the moisture in the blast below 1 grain. At Cardiff the furnaces were run continuously for long periods on a moisture content well below 1 grain; in fact, 0.75 grain per cu. ft. was the figure aimed for, and generally between 0.75 and 1.00 grain was obtained. He was therefore inclined to question Mr. Lewis' explanation of the falling off of his quality with low moisture as being due to loss of catalytic action when the moisture fell below 1 grain. That did not seem credible. Did it require as much as 1 grain of water per cu. ft. of air to bring about that degree of catalytic action which was generally recognised as necessary for the normal reduction of iron ore and combustion of carbon? Did not normal combustion take place with air containing under 1 grain of water per cu. ft.? It would seem so, and not only in the blast-furnace. Was there any difficulty in starting a fire on a domestic hearth on a cold dry night, or in starting one out-of-doors when the cold dry atmosphere certainly contained well under 1 grain of moisture per cu. ft.?

He asked if Mr. Lewis had noticed any increase in the rate of driving during those periods when the moisture was very low in comparison with that at which he had aimed and for which his furnace was burdened? It was noticeable at Cardiff that the furnaces drove faster with the same volume of blast when the moisture was low compared with the standard dry air moisture. If Mr. Lewis' furnace was burdened for a moisture of $1\frac{1}{4}$ grains, and the moisture fell to 0.75 grain, it was quite possible that the furnace might have driven so much faster as to throw it off quality—particularly with a furnace of the type with which he was operating, that is, a small furnace operating with coal. If that was not noticed it was, perhaps, because the engines were slowed down as soon as the quality changed, as was the custom in some practice, before the cause of the change in quality—which might have been faster driving, and which would affect a furnace of that size more quickly than a larger furnace—had been determined. He was inclined to the opinion that the explanation given by Mr. Lewis was not the correct one.

MR. E. C. EVANS (London) thanked the author for having analysed the results of his work by the method suggested by Mr. Bailey and himself.¹ By maintaining a constant moisture content in the blast, Mr. Lewis had eliminated a variable which was extremely difficult to ascertain in normal operation. Several of his own friends—British, Continental, and American—had from time to time made detailed

¹ *Journal of the Iron and Steel Institute*, 1928, No. I. p. 53.

criticisms of the mathematical equations put before the Institute, and they also frequently put forward a series of blast-furnace results which seemed to indicate that those equations were not correct. Mr. Bailey and he had become so accustomed to using those formulæ that when they got a series of blast-furnace results of that type they immediately suspected the existence of another factor, which frequently became evident on further analysis. Mr. Lewis' results had brought out a factor which had never before been anticipated—namely, the variation in radiation in summer and winter. There was a definite difference in the amount of heat lost to the atmosphere by Mr. Lewis' furnace during the hot months and the winter months. He was very interested to learn that Mr. Lewis had taken the rather heretical step of insulating the top of his furnace. It should do good if Professor Bone's work was correct. The rate of reaction of the ore-reducing gas should be increased by the maintenance of a higher temperature in the upper portion of the furnace. One looked forward with considerable interest to the results that would be obtained.

Referring to the optimum dryness mentioned by Mr. Reese, he said there was no doubt, from the analysis of Mr. Lewis' results, that there was a degree of optimum dryness, and that mathematical analysis did take into consideration the effect of the rate of driving and the other variables which Mr. Reese had mentioned. The work which was at present being done by Professor Bone for the National Federation of Iron and Steel Manufacturers promised to throw light on that subject. Professor Bone had found that the reduction of the moisture or the hydrogen in a reducing gas, down to a point, increased the rate of reduction of an ore. Below that point the rate of reduction was enormously retarded, and, with absolutely dry reducing gas, the probability was that no reducing effect at all would take place; so that, if those experiments were substantiated, below a certain degree of moisture the rate of reduction in the blast-furnace would undoubtedly be reduced, with a consequent increase in the fuel consumption.

Mr. LEWIS, in reply, said that Mr. Hutchinson had been kind enough not to offer any criticism of the paper, but only commendation. Professor Desch had asked a very important question about the life of the gel. The gel examined two or three months ago exhibited no appreciable variation from the first sample which had been taken a few weeks after the plant had started. No gel had been added to the plant; it had not been necessary. A little had been taken out, because it was found that they had more than they needed. A certain amount of tar certainly got through the by-product recovery plant, because, as was known, there were large quantities of tar in those particular gases before cleaning, and it was very difficult to eliminate the very last traces. They activated direct with the blast-furnace gas, but it was found that the hydrocarbons, in so far as they were deposited on the gel and caused a slight discoloration, were very easily removed. By

raising the activating temperature 10° or 15° C. the whole of the discoloration was removed. Tests taken under those conditions showed in some cases that the gel was rather better after such treatment than it had been before.

With regard to blast-furnace coke, he saw no reason why the advantages should not be as great with coke furnaces as with coal furnaces, except that with coke furnaces they would not get the extra present of additional oil from the coal. That was something which had been hoped for, but which had not been expected in anything like the quantities in which it was being obtained. As a matter of fact, the addition of oil paid the royalty—which was very nice. That result would not be obtained on the coke furnace. Otherwise he saw no reason why the advantages should not be quite as great on coke furnaces—and he thought that had been proved, first by Gayley's results, and secondly by Mr. Reese's results to which he had referred.

Mr. Harbord had asked about the cost of the plant. He was afraid he was not at liberty to give the cost without first consulting the company by whom he had been formerly employed at Wishaw. Anybody who was interested could no doubt get an estimate of the cost from the makers of the plant which would enable them to make up a balance sheet. He could say, however, that he was quite satisfied that in a very few years the whole cost of the plant at Wishaw would have been wiped out by the savings.

In reply to Mr. Reese on the question of the optimum dryness, he doubted very much indeed whether any domestic fire had ever had air supplied to it—at least in latitudes south of the extreme North of Scotland—with anything approaching 1 grain of moisture; it was only in extremely cold weather that the atmosphere went below 1 grain, and in the case of a house, there was always a lot of moisture taken up from the inmates, apart from anything else. It was very difficult indeed to get natural air below 1 grain. He had noticed, in looking through Gayley's results obtained some years ago, that there was not a single figure below about 0.98 grain.¹ The moistures which had apparently caused trouble at Wishaw had been considerably below that. Now that they had learned from experience, if the atmospheric moisture went below 1 grain, the dry blast plant was blocked off altogether so that no air at all could be drawn from it, because under such conditions—atmospheric moisture below 1 grain—the dry blast plant gave moistures in the neighbourhood of 0.02 grain.

Mr. Reese had asked if there was any speeding up of the furnace when the moisture became very low. The contrary had been the experience, namely, that along with the colder iron and the white iron casts a definite slowing down of the furnace occurred when the moisture went considerably below 1 grain.

It was interesting to note that in the results published by Mr. Reese

¹ *Journal of the Iron and Steel Institute*, 1904, No. II, p. 296.

a higher fuel consumption was given for several of the weeks when the moisture was lowest than for those weeks when the moisture was about 1 grain per cu. ft.¹

This paper was also presented at the Additional Meeting held at Glasgow on May 9, 1929.

The CHAIRMAN (Mr. R. Hamilton) said the subject dealt with had given rise to a great deal of interest in the Glasgow district since Mr. Lewis had first taken it up some time ago. He knew that the experiment at Wishaw was being closely watched by various people who wished to be sure that everything was all right before possibly taking further steps. He would like to ask Mr. Lewis a question about the optimum dryness, to which he had referred in his first paper. At that time (1927) the moisture in the blast had only once gone below 1 grain, and he had quickly retraced his steps. He had intended to make further trials; he had evidently done so, and the cooling of the furnace had been rapid. He (Mr. Hamilton) desired to know if any opinion had been formed as to the cause of that. It was known, of course, that certain reactions did not readily take place between gases when they were thoroughly dry, and he had in mind an experiment of a very extreme nature in which the gases were thoroughly dry and reaction did not occur. He supposed that even going below 1 grain might have a retarding effect.

Mr. SETON KARR replied that Mr. Hamilton had correctly interpreted Mr. Lewis' opinion with regard to the amount of moisture in the blast. There was one point he had omitted to mention in the paper. In the last column of Table I. the percentage saving in fuel was given as 5.45 per cent.; that must be taken as the saving obtained under the atmospheric conditions prevailing in the Wishaw district. In considering the value of a dry blast plant, account must be taken of the atmospheric conditions prevalent in the district where it was proposed to instal it.

¹ *Journal of the Iron and Steel Institute*, 1920, No. II. p. 112.

THE A.I.B.¹ SINTER PLANT AT MESSRS. GUEST, KEEN AND NETTLEFOLDS, LTD., CARDIFF WORKS.²

BY W. E. SIMONS (CARDIFF).

INTRODUCTION.

ALTHOUGH there are several sinter plants in Great Britain, the sintering of iron ores has not received the attention it deserves.

The evil effects of fine materials in the blast-furnace are too well known to be further elaborated upon here. The preparation of materials prior to their introduction into the blast-furnace is one of the outstanding features of modern American and Continental practice. F. H. Willcox³ has stated that by crushing and screening ore, coke, and limestone it is possible to increase the output of a blast-furnace by about 12 per cent.

It is the practice at some Continental plants not to put anything into the blast-furnace smaller than an inch cube. Besides higher outputs and lower fuel consumptions, less flue-dust is made; lower blast pressures, less slipping and less sticking occur, and more regular working of the blast-furnace is obtainable. The preparation of materials in Great Britain has been badly neglected; very few plants have any crushing or screening plants.

Sinter itself is ideal for blast-furnace use, for it is very porous, with large surfaces exposed to the reducing gases, and is fairly fusible. Good sinter should be strong physically, porous and free from fines; in appearance it is like hard boiler clinker, and is dark blue in colour.

The result of separating out the fine ores by screening and sintering at the Cardiff Works has been the attainment of a consistently higher output, and coke consumption has been reduced by about 1 cwt., the amount of sinter used varying from

¹ Allmänna Ingeniörsbyrån, Stockholm.

² Received January 18, 1929.

³ *Iron Age*, 1928, vol. cxxi. pp. 1011-1012.

16 to 25 per cent. of the ore burden. In addition to separating out the fines, the lumpy ore and limestone are crushed to a uniform size.

DESCRIPTION OF SINTER PLANT.

The general layout of the sinter plant is shown in Fig. 1 (Plate III.).

All the material is brought to the sinter plant in hopper-bottom wagons ; they are discharged into a bunker, from which the material is elevated on an inclined belt and can be passed into either the crushing plant or, if sufficiently fine, into the bunkers. This belt passes over a magnetic pulley for the removal of tramp iron.

Crushing Plant.—As a crushing plant is common to all sinter installations, it is not necessary to describe it in detail. The coke and ore crushing plants consist of one primary roller crusher and one primary jaw crusher respectively, each followed by two secondary roller crushers. From the crushers the materials are conveyed to their respective bunkers by means of rubber belts.

Bunkers.—There are two rows of bunkers, six ore bunkers in one row, and, adjoining them, one large bunker for flue-dust and a large one for coke. The flue-dust and coke bunkers each have twice the capacity of an ore bunker ; one of the ore bunkers is used for “ return fine sinter,” which is sintered again.

Each bunker is emptied by means of an apron belt, driven by a ratchet mechanism. To regulate the amount of material leaving each bunker there is a vertical slide, which is adjusted by a ratchet-wheel and a pawl. The emptying gear on the coke and flue-dust bunkers is smaller than on the ore bunkers.

The ore, the coke, and flue-dust are discharged on to horizontal rubber belts which transfer them on to an inclined belt running into the sinter house.

Sinter House.—Briefly, the operation of sintering consists of mixing fine iron ore, coke, and flue-dust ; this mixture is placed in a circular steel pan, and ignited by means of oil burners, a motor-driven fan drawing air through the pan. When burnt, the fine materials have fused into a dark blue clinker. The pan is then tipped, and the sinter is conveyed into a railway wagon ready for use.

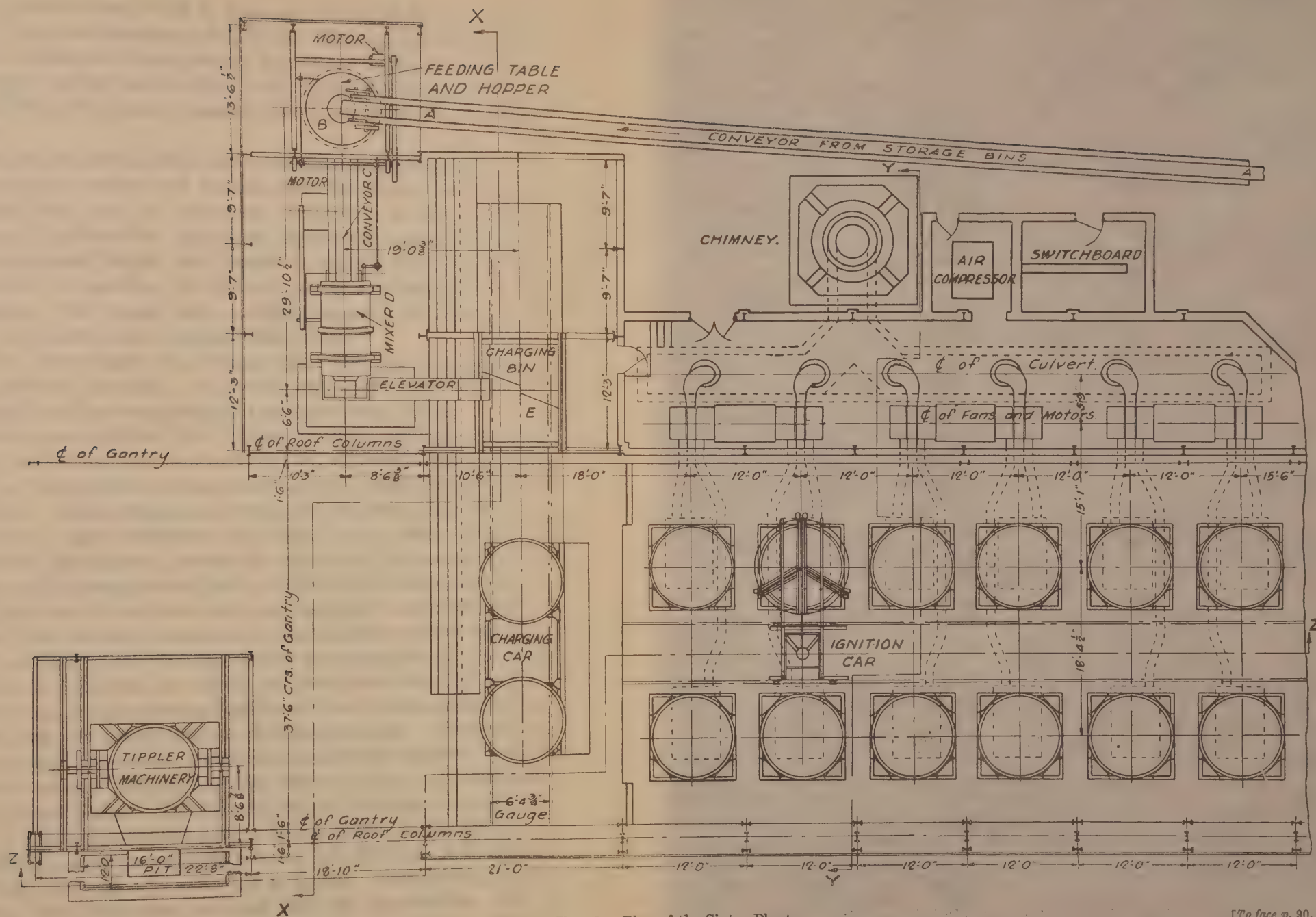


FIG. 1.—Plan of the Sinter Plant.

[To face p. 90.]

The sinter house is 146 ft. long, and the width from the centre lines of the roof columns is 40 ft. 6 in. Running the whole length of the building is a crane gantry, the span of which is 37 ft. 6 in.; the height of the rails is 21 ft. 9 in. above the main floor level. Fig. 5 (Plate IV.) gives a general view of the interior of the sinter house.

On one side of the sinter house is an annexe, in which is situated the receiving hopper and feeding gate, the mixer, elevator, and charging bin; on the same side, farther down, the fan house adjoins. On the other side of the building is a crane gantry, of the same span, height, and length as that in the sinter house; it is used for handling the finished sinter, and under it are two railroads. The cranes have a lifting capacity of 10 tons, and each is provided with a special lifting beam.

The sinter plant is a 12-pan unit; the pans are placed in two rows of six each. At present only eight pans have been installed, and the remaining four are now being put in.

Each pan is 2.6 m. (8 ft. 6 $\frac{3}{8}$ in.) in diam., 325 mm. (12 $\frac{7}{8}$ in.) deep, and holds from 1.5 to 1.75 tons of finished sinter. It is made of four ribbed circular steel castings, machined and bolted together. Two sections have trunnions for lifting, and the other two have a short additional rib, which is used when the pan is placed in the tippler. Across the bottom of the pan are bolted four equally spaced bearer bars, on which the firebars are placed; the latter are of cast iron, and are arranged to interlock on the bearer bars, so as to prevent any displacement of bars when the pan is turned over. On the inside circumference of the pan a number of steel ribs are cast on an inch above the firebars, and under them are placed curved mild steel bars of rectangular section which lock the firebars around the circumference. These locking bars are kept in position by studs screwed into the firebars. Bolted on the bottom of the pan is a dish, 300 mm. (11 $\frac{1}{8}$ in.) deep, made of mild steel plates. Between the pan and the dish is an asbestos ring to make an air-tight joint. In the middle of the bottom of the dish is a steel casting with a bored hole 320 mm. (1 ft. 0 $\frac{1}{8}$ in.) in diam., through which the air is drawn. This casting fits on to the valve connecting the pan with the fan suction. Fig. 2 shows the sequence of the materials into the sinter pan. Fig. 3 is a sectional elevation through the sintering bay.

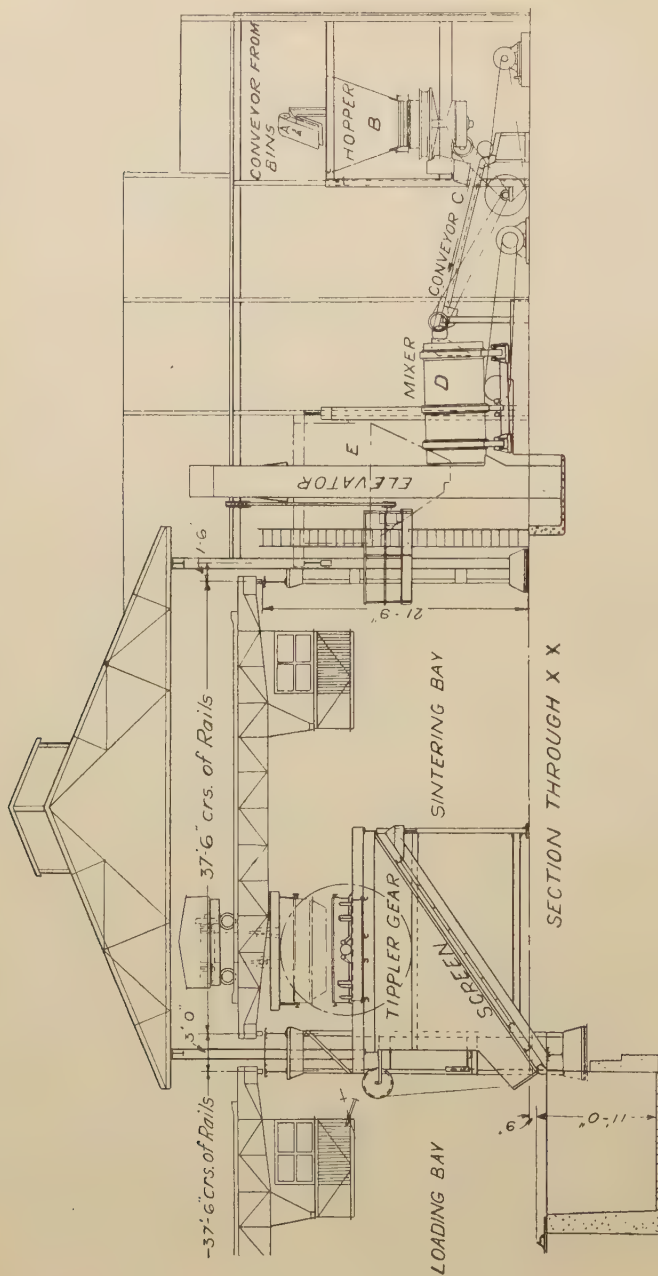


FIG. 2.—Sectional Elevation.

The material to be sintered is brought up by an inclined belt (A) from the bunker house, and is put into a circular bunker (B) ;

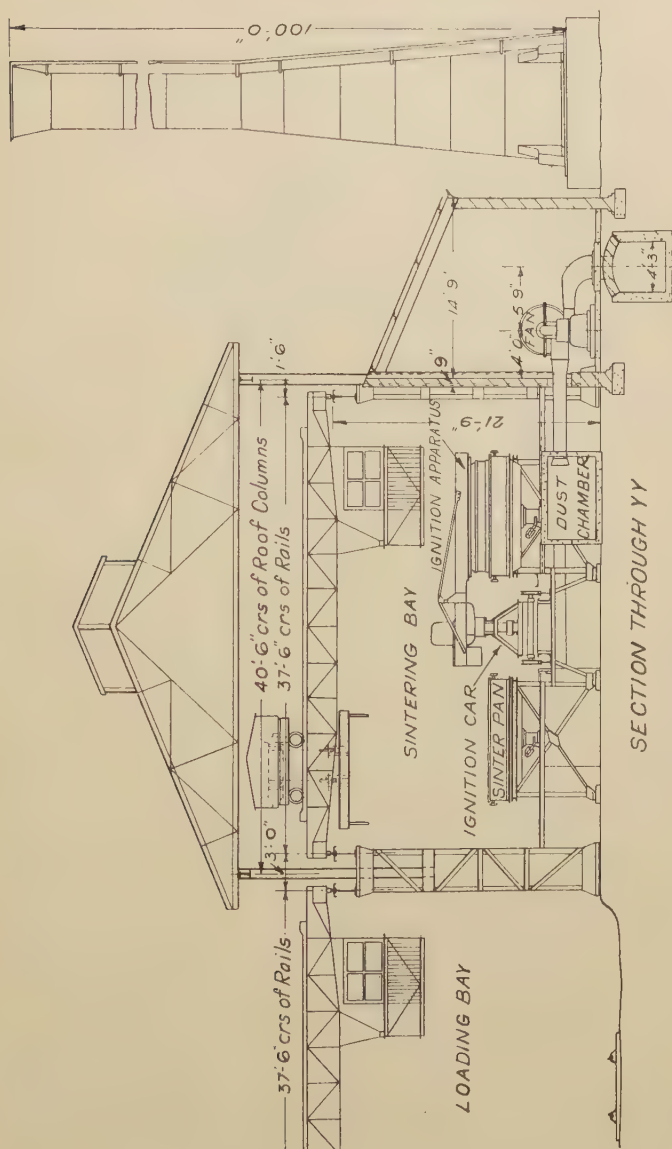


Fig. 3.—Sectional Elevation through the Sintering Bay.

the latter is emptied by a circular revolving gate and a plough, and the material is passed on a rubber belt (*C*) to the mixer (*D*), which consists of a steel drum 1.5 m. (4 ft. 11 $\frac{1}{8}$ in.) in diam., and is fitted inside with angle irons to facilitate the mixing. The mixed material is discharged into an elevator and taken up into the charging bunker (*E*). The elevator and charging bunker are shown in Fig. 4.

The charging car, which passes under the charging bunker, can accommodate two pans; an empty pan is filled while a full one is being tipped. It is driven by a 10-H.P. motor, and by means of clutches it can travel or rotate either pan. An empty pan is placed on the charging car, and a small quantity of rubbly return sinter is put on the bottom of the pan for bedding; the pan is then brought under the charging bunker (*E*). It is then filled by opening the special electrically operated segment gate fitted to the bunker; by revolving it even filling is attained. When the pan is full the charging car moves out from under the bunker and comes under the crane gantry. A little anthracite duff or coke breeze is thrown over the pan to facilitate the ignition. Fig. 6 (Plate V.) shows the charging bunker and a pan being filled.

The overhead crane brings back an empty pan from the pan tippler and puts it on the charging car; the latter with a full pan and an empty one is shown in Fig. 5. The crane then places the full pan in one of the stands, which are built up of mild steel sections riveted together. When the pan is lowered into position a valve automatically opens, and suction from the fan is applied to the pan; similarly, when the pan is lifted this valve automatically closes and shuts off the fan suction.

Under the stands are the dust chambers, in which collects any dust which may be drawn through by the fan. The chambers consist of reinforced concrete boxes, from each of which a cast-iron pipe conducts the gases to the fan.

The pan is then ignited by means of an ignition car, which runs on a track of 6 ft. 4 $\frac{3}{4}$ in. gauge situated between the two rows of pans. The ignition car consists of a rectangular framework of mild steel sections riveted together and mounted on four wheels. On top of a king-post fitted in the middle of this framework is fixed a beam, at one end of which the ignition apparatus is suspended, and at the other end is a cast-iron balance weight.

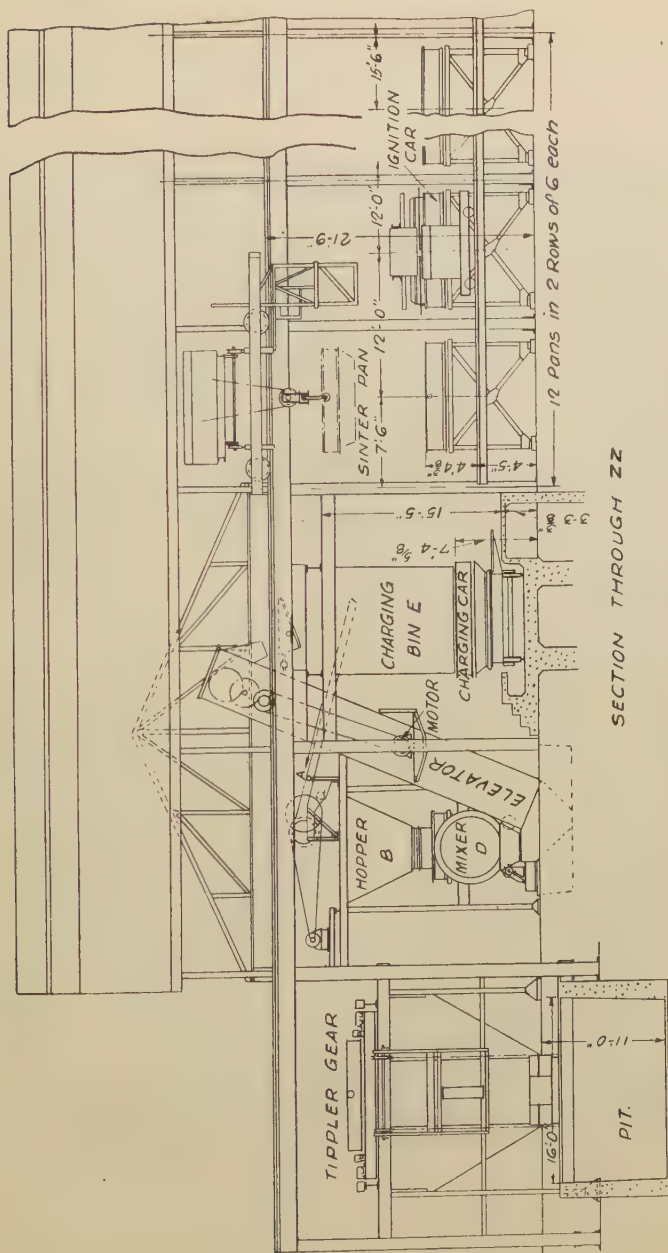


FIG. 4.—Sectional Elevation showing the Elevator and Charging Bunker.

Between the ignition apparatus and the balance weight the fuel oil tank is placed. The ignition car is driven by a 5-H.P. reversible motor, and by means of clutches either the car can be made to travel or the beam can be rotated.

The ignition apparatus itself consists of a circular hood, the inside diameter of which is the same as that of the pan ; by means of a screw arrangement it can be lowered or raised. Around its circumference are three burners, equally spaced, which are so arranged that they can be oscillated in unison to ensure that the whole surface of the pan is covered by the flames.

The ignition is accomplished by means of fuel oil and compressed air. The air, at a pressure of 75 lb. per sq. in., is supplied by a 2-stage Sentinel air compressor, which is situated in a building adjacent to the fan house. A flexible hose is connected on to a T-piece on top of the oil tank, in order to put the oil in the tank under pressure. The compressed air then passes through a set of three small tubes across the hood to the three burners ; as each burner is movable, a length of this tubing has to be flexible. The oil under pressure is conducted to the burners by a similar set of tubes. On each burner there are two regulating cocks, one for air and the other for oil.

To ignite the pan the hood is first lowered over the pan. The compressed air hose is then connected to the supply ; the compressed air cocks on the burners are always left open. The oil is then turned on at each burner and lit with a torch. To obtain a uniform ignition throughout, the burners are oscillated so that every portion of the pan is covered by the flames.

The time of ignition is from 1 to 2 min. When the ignition is completed, the oil is first turned off ; the hood is then raised, the compressed air turned off, and the hose disconnected. The time of sintering is from 1 to $1\frac{1}{2}$ hr., depending upon the materials being sintered. The oil consumption is 0.6 gal. per ton of finished sinter.

Fans.—The fans are placed in a building adjoining the sinter house. One motor drives two double-compartment fans, and each compartment draws from one pan. There are eight pans installed, and there are four fans direct-coupled to two fan motors, which are each of 135 H.P. and rotate at a speed of 2300 r.p.m. The exhaust gases pass from the fan through a



FIG. 5.—General view of the interior of the sinter house.

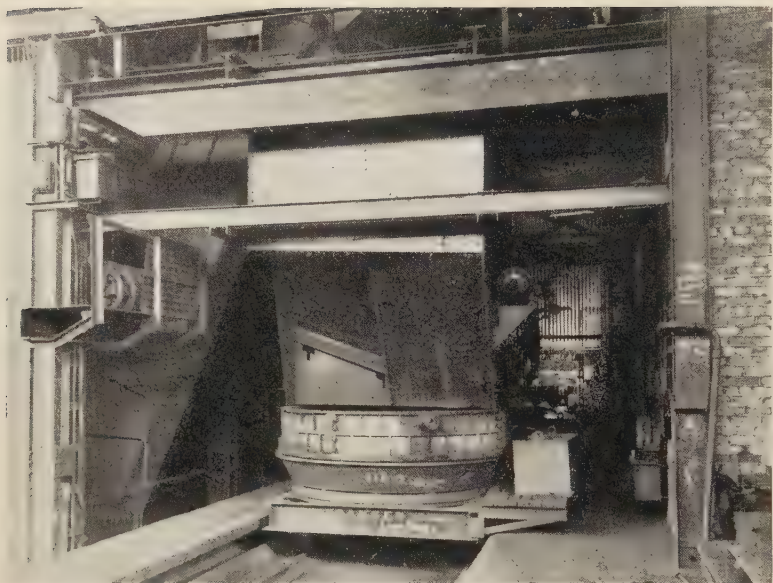


FIG. 6. —Charging bunker with pan underneath being filled.

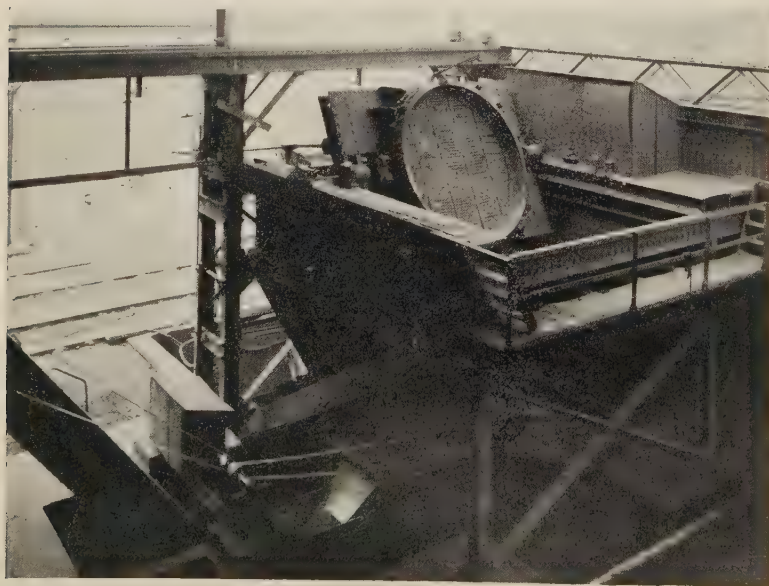


FIG. 7.—Tippler gear.

tunicle pipe to the chimney flue. The fan suction is about 30 in. at the commencement of sintering, and decreases as the pan is sintered.

Tippler Gear.—When the pan is sintered it is conveyed by the overhead crane to the tippler gear, shown in Fig. 7 (Plate V.) with a pan fixed in it. The tippler gear, consisting of a rectangular frame into which the pan fits, is fixed on top of a bunker for containing the finished sinter; the frame is rotated by an electric motor, and the sinter drops out of the pan. To keep the pan in the frame there is a locking device, which is automatically worked by the crane and is absolutely foolproof and reliable. When the crane driver has placed the pan in the tippler he moves back in the crane to the tippler controller, placed about 10 ft. from the tippler and so arranged that he can work it by simply putting his hand out of the cab window. After the pan is tipped the crane takes the empty pan away and lowers it on to the charging car to be filled again.

The receiving bunker for the finished sinter has a sloping bottom—so that the sinter will easily empty out of it—consisting of cast-steel screening bars of $\frac{5}{8}$ -in. mesh. Through these screens the rubble and fine sinter pass into a rotary screen which has $\frac{3}{8}$ -in. diam. holes. The rubble is discharged to an elevator which puts it into a small bunker; it is then used for bedding. The main bunker discharges directly into a skip. The fines which are screened out pass into a bunker underneath the sinter bunker. In front of the latter is a rectangular pit, into which is lowered a rectangular skip suspended from the outside overhead crane.

The door on the tippler bunker is operated by compressed air; the controlling valve can be operated from the cab of the outside crane. The skip is placed in front of this door, and when it is opened the finished sinter falls into the skip. The gate on the fines bunker is under the other gate.

To empty the fine sinter bunker the skip is lowered to the bottom of the pit, and the gate is also opened from the crane cab. Underneath this overhead crane there are two parallel railroads, on which the empty hopper-bottom wagons are put; the overhead crane fills them.

If the finished sinter is very hot it can be sprayed with water while in the skip, prior to being tipped. The fine sinter is put

into wagons, and is passed through the plant to be again sintered. This arrangement of disposing of the finished sinter has been found cheap and efficient.

The power consumed is 15 to 16 kw. per ton of sinter produced, excluding the power required in the crushing plant.

PRACTICE OF SINTERING.

While the purpose of sintering is the agglomeration of fine materials, the process is greatly facilitated by the presence of a fair amount of small rubbly material, up to $\frac{1}{4}$ in. cube ; should the material be above this size it is necessary to crush it, as it is too big to fuse into sinter.

All the coke breeze is crushed down to $\frac{1}{4}$ in. cube ; it is advantageous for the coke breeze to be rubbly, as otherwise it burns too quickly.

All the materials as they are delivered into the mixer are usually dry. Inside the mixer is a fine spray of water for wetting the material as it is mixed. The mixed materials should contain about 15 per cent. of water ; this is necessary to keep the mixture open while it is being sintered in the pan.

All the materials should be free from lime ; lime and silica fuse together at a low temperature, which causes the materials to fuse into a dense mass that sticks in the pans. Similarly, if there is too much carbon in the sinter material the mass melts and the resulting sinter is hard and dense and resembles mill cinder. It also tends to stick in the pans. The amount of carbon necessary in the sinter mixture varies with the materials under treatment. When sintering iron ore, pyrites, and flue-dust, about 7 per cent. of carbon is required. A small amount of anthracite or coke breeze is thrown on top of the pan prior to ignition. This ensures good ignition and reduces the amount of fines made to a minimum.

Particulars of Materials Used.—The analyses of the materials used are given in Tables I. and II.

The coke breeze used is the screenings from coke-ovens, and the analysis is similar to that of ordinary coke, only that the moisture and ash content are usually a little higher.

All iron ores, whether hematites or magnetites, make good sinter and present no difficulties in sintering, provided that the

TABLE I.—*Analyses of Iron Ores.*

	Fine Obregon Ore.	Spathic Ore.	Spathic Ore.	Tamera Ore.	San Miguel Ore.	Burnt Pyrites.		
	%	%	%	%	%	%	%	%
Moisture .	12·80	1·00	0·62	5·2	9·10	7·5	12·4	15·0
Iron .	40·46	56·82	54·91	51·9	47·32	56·42	51·6	50·15
Manganese .	...	...	...	...	...	...	...	...
Silica .	11·30	...	9·54	...	...	...	...	...
Alumina .	6·95	...	0·99	...	...	...	...	...
Insol. residue .	13·86	7·93	...	4·26	9·56	1·85	8·0	7·7
Lime .	0·17	1·05	2·88	0·76	...	0·80	...	...
Magnesia .	Trace	3·05	4·07	0·26	...	0·20	...	...
Phosphorus .	0·04	0·013	0·016	0·046	0·017	0·01	0·014	0·022
Sulphur .	0·052	0·43	0·519	0·082	0·023	0·40	2·7	2·80
Copper .	...	...	...	...	...	0·32	...	0·13

Complete Analysis of Holton Heath Burnt Pyrites.

Moisture .	0·85	Sulphur .	1·43
Iron .	58·13	Phosphorus .	0·013
Insoluble residue .	10·21	Manganese .	Nil
Silica .	9·17	Copper .	1·18
Alumina .	1·19	Lead .	Trace
Lime .	1·28	Loss on ignition .	2·80
Magnesia .	0·45		

TABLE II.—*Analyses of Flue-Dust.*

I. and II.—From blast-furnace dust-catcher.

III.—From gas main between blast-furnace and gas-washer.

IV.—From dust-catcher adjacent to gas-cleaning plant.

	I.	II.	III.	IV.
	%	%	%	%
Moisture .	12·00	Dry	0·80	0·10
Ferrous oxide .	21·70	12·60	26·14	29·03
Ferric oxide .	37·60	49·01	30·24	36·54
Total iron .	43·12	44·1	48·7	48·15
Residue .	7·24	10·9	9·92	...
Lime .	...	3·30	2·97	2·58
Magnesia .	...	1·50	1·81	1·62
Sulphuric anhydride .	...	1·02	0·99	1·21
Phosphoric acid .	...	0·082	0·072	0·065
Loss on ignition .	13·6	14·80	11·30	7·50
Sulphur .	...	0·41	0·40	0·49
Phosphorus .	...	0·036	0·032	0·029
Carbon .	12·20	12·48	10·44	7·00

NOTE.—The carbon content of flue-dust is highest near the furnace; as the flue-dust is deposited farther away from the furnace the carbon content decreases.

iron or silica contents are not extremely high. Burnt pyrites is usually more refractory than iron ores, and it requires more coke. It often contains a large percentage of sulphur, especially when it has a large portion of rough material, as the sulphur is then not properly burnt out. However, in the process of sintering, most of the sulphur is burnt out. Purple ore presents no difficulties in sintering and makes good sinter.

Flue-dust is one of the most difficult materials to deal with. However, as a blast-furnace makes much of this material, it has to be used, and it is very cheap. The Cardiff flue-dust is rich in iron and carbon, and can be considered as both an ore and a fuel ; the excess carbon replaces some of the coke breeze. The trouble with flue-dust is that the carbon content is very variable, so that the mixture may at one time show an excess of carbon, while a very short time after it is deficient in carbon. The sinter mixture should never contain more than 30 per cent. of flue-dust, as the sinter is liable to be very irregular in quality.

Flue-dust should never be used directly it comes from the blast-furnace. It has been found in practice that it sinters much better when it has been stocked out in the open and " weathered " for several months.

When a blast-furnace has been slipping badly, large lumps of coke, up to 4 in. cube, are often found in the flue-dust. It is impossible to separate them out, so the flue-dust is put into the sinter mixture with them in. It has been found that these lumps of coke give no trouble at all, and do not cause any overheating. They simply pass through the sinter process without being burnt.

Roll scale sinters very easily, and, owing to its high iron content, it considerably enriches the resulting sinter.

The amount of return sinter made is about 15 to 20 per cent. This material is very easy to sinter, and its presence in the sinter mixture is advantageous, as it tends to keep it porous.

OPERATING RESULTS.

The Cardiff plant is worked continuously, Sundays and holidays included. Three 8-hr. shifts are employed ; this is necessary, because the blast-furnace works continuously. Details and results of a month's working during October 1928 are given in Tables III. and IV.

TABLE III.—Analyses of the Sinter Mixture and the Resulting Sinter from September 14 to October 12, 1928.

Mixture.								Sinter.								
Date.	Moisture. %	Carbon. %	Iron. %	Insol. Residue. %	Sulphur. %	Phos- phorus. %	Loss on Ignition. %	Date.	Iron. %	Insol. Residue. %	Silica. %	Alu- mina. %	Lime. %	Mag- nesia. %	Sulphur. %	Phos- phorus. %
14-9-28	15.80	7.00	43.95	7.93	0.40	0.021	8.16	14-9-28	60.50	10.98	8.72	...	...	...	0.030	0.030
17-9-28	14.80	7.14	44.13	7.83	0.43	0.023	8.00	17-9-28	60.00	11.68	8.90	...	...	...	0.086	0.028
18-9-28	14.50	6.00	45.31	8.44	0.39	0.024	7.52	18-9-28	59.80	12.68	8.80	...	...	...	0.055	0.031
19-9-28	15.20	6.40	43.92	8.14	0.39	0.023	7.90	19-9-28	59.00	12.60	8.60	...	...	...	0.068	0.031
20-9-28	15.40	4.84	44.42	10.40	0.37	0.023	6.97	20-9-28	58.70	12.80	8.30	...	0.98	1.98	0.066	0.030
21-9-28	14.35	5.10	45.40	8.40	0.42	0.019	7.60	21-9-28	58.80	13.18	8.90	...	...	...	0.054	0.031
24-9-28	14.30	5.80	45.15	8.30	0.31	0.014	6.90	24-9-28	57.80	13.88	9.40	...	...	...	0.030	0.028
25-9-28	14.50	6.40	43.31	9.40	0.33	0.015	7.60	25-9-28	56.80	14.60	7.90	...	...	...	0.037	0.028
26-9-28	15.40	6.00	44.80	8.30	0.43	0.015	7.70	26-9-28	57.30	14.58	8.60	...	...	...	0.054	0.031
27-9-28	13.90	6.50	44.72	10.32	0.37	0.012	8.22	27-9-28	56.60	15.76	9.80	...	0.76	1.47	0.047	0.031
28-9-28	14.50	6.40	44.46	8.80	0.38	0.014	7.96	28-9-28	57.60	14.60	9.12	...	...	...	0.041	0.030
1-10-28	14.50	6.00	45.31	8.55	0.41	0.017	7.69	1-10-28	58.00	13.64	9.64	...	...	...	0.047	0.024
2-10-28	15.40	4.77	45.17	8.25	0.40	0.019	7.40	2-10-28	58.20	13.52	9.40	...	...	...	0.066	0.030
3-10-28	16.30	6.10	43.85	8.80	0.39	0.017	6.95	3-10-28	59.40	14.06	10.00	...	...	...	0.033	0.032
4-10-28	14.10	6.41	44.89	8.68	0.49	0.023	7.56	4-10-28	58.50	13.60	9.20	...	...	...	0.071	0.032
5-10-28	14.70	6.02	45.21	8.39	0.49	0.026	7.67	5-10-28	61.50	12.14	9.26	...	1.40	1.87	0.081	0.032
8-10-28	14.20	6.80	44.87	9.19	0.39	0.019	7.80	8-10-28	58.90	13.26	8.86	...	...	...	0.079	0.030
9-10-28	14.70	5.40	45.37	9.16	0.44	0.022	6.70	9-10-28	57.00	15.68	10.60	...	...	...	0.078	0.032
10-10-28	14.40	6.21	44.68	9.58	0.28	0.024	6.76	10-10-28	58.80	13.90	9.00	...	...	...	0.021	0.032
11-10-28	14.50	6.13	45.48	9.23	0.31	0.019	6.74	11-10-28	59.10	13.38	8.75	...	...	...	0.025	0.030
12-10-28	14.10	6.46	35.69	14.55	0.17	0.047	14.96	12-10-28	54.30	18.92	12.60	5.70	0.60	1.30	0.046	0.075
Shift 2-10. Obregon Mixture								Sinter ex Obregon Fines								
12-10-28	13.30	5.00	46.54	8.80	0.37	0.023	6.78	12-10-28	59.20	12.98	8.68	...	1.50	1.98	0.033	0.030
Shift 6-2, 10-6																

TABLE IV.—*Operating Results.*

Date.	No. of Fans Sintered.	Total Time Lost.	Average per Pan.	Sinter Made.		Fines.		Analysis of Mixture. %. Weekly Average.
1928.		Hr. Min.	Tons.	Tons.	Cwt.	Tons.	Cwt.	
Sept. 29	135	2 10	1.63	220	5	53	7	Spathic . . 48.90
30	126	3 55	1.61	203	4	54	16	Pyrites . . 15.54
Oct. 1	146	...	1.55	226	7	57	8	Flue-dust . . 14.79
2	152	...	1.58	240	7	81	4	Return fines . 20.76
3	152	...	1.52	231	19	76	9	
4	150	...	1.64	245	13	67	7	99.99
5	140	1 30	1.55	223	7	59	19	Coke breeze on mixture, 6%
Total .	1001	7 35	1.58	1591	2	450	10	
Oct. 6	152	...	1.60	243	2	62	1	Obregon . . 1.64
7	141	2 30	1.67	235	13	55	12	Spathic . . 48.21
8	141	0 10	1.54	217	5	66	17	Pyrites . . 15.66
9	150	0 30	1.47	220	6	81	1	Flue-dust . . 13.92
10	140	0 55	1.52	213	13	67	15	Return fines . 20.56
11	146	0 55	1.55	226	11	49	12	
12	135	0 50	1.57	211	15	63	2	99.99
Total .	1005	5 50	1.56	1568	5	446	0	Coke breeze on mixture, 6.59%
Oct. 13	149	...	1.60	238	8	54	13	Spathic . . 53.12
14	142	0 30	1.54	220	11	54	0	Pyrites . . 14.08
15	146	0 20	1.65	240	15	65	12	Flue-dust . . 14.22
16	94	9 45	1.57	148	1	57	15	Return fines . 18.58
17	134	2 45	1.57	210	13	57	16	
18	91	9 0	1.57	143	1	25	3	100.00
19	83	10 25	1.59	132	5	48	7	Coke breeze on mixture, 6.29%
Total .	839	32 45	1.59	1333	14	363	6	
Oct. 20	141	1 10	1.62	233	13	46	5	Spathic . . 64.71
21	144	1 25	1.66	239	18	54	18	Flue-dust . . 16.14
22	156	...	1.61	252	2	54	9	Return fines . 19.14
23	140	1 0	1.66	233	2	71	2	
24	146	1 0	1.63	238	7	46	3	99.99
25	140	0 55	1.62	227	4	51	19	Coke breeze on mixture, 6.16%
26	142	2 15	1.71	242	5	61	6	
Total .	1009	7 45	1.65	1666	11	386	2	
Oct. 27	152	0 45	1.53	232	11	63	16	Obregon . . 8.25
28	154	...	1.64	252	19	74	2	Pyrites . . 1.97
29	142	1 45	1.55	220	16	57	5	Tamera . . 10.92
30	144	0 55	1.54	222	8	68	7	Spathic . . 45.17
31	136	1 5	1.50	204	7	45	0	Flue-dust . . 16.46
Nov. 1	91	8 45	1.44	121	9	47	17	Return fines . 17.22
2	140	2 0	1.51	212	5	67	19	
Total .	959	15 15	1.53	1466	15	424	6	99.99
								Coke breeze on mixture, 7.26%

DISCUSSION.

Mr. DAVID E. ROBERTS (Cardiff) congratulated Mr. Simons on the presentation of his first paper. There was nothing to-day which was of greater interest to blast-furnace people than the dressing of materials, and, in particular, the sintering of fine stuff generally. It was admitted by all blast-furnace men that the charging of fine material into a furnace was a great mistake. On the Continent and in America all fines, both ore and coke, were separated out. All that fine stuff was put through a process similar to that which Mr. Simons had described, thus making valuable material with which later to feed the blast-furnace.

There were two or three types of sintering machines. The two best known were the old Dwight-Lloyd and the Greenawalt. The one of which Mr. Simons had spoken was a modification of the latter—and an improvement upon it, in his own opinion. The Greenawalt method was worked with a series of large rectangular pans on trunnions. In the arrangement described by Mr. Simons the pans were of circular form; they were picked up and carried away to a separate building for manipulation, cleaning, discharging, and so on. It was an excellent method. The whole plant was a great success, and he was sure that a study of it by members interested in the question of sintering would result in great benefit.

Mr. L. BARREIRO (Bilbao) said Mr. Simons' paper was very interesting to those engaged in the subject in Spain, because some of the ores in that country were fine. He was glad that Mr. Simons was encouraging British engineers to use those ores in Great Britain. The plant at Cardiff appeared to be a very good one indeed, and he congratulated Mr. Simons, and thanked him for his valuable paper.

Mr. F. W. HARBORD, C.B.E. (Past-President), remarked that he had had the pleasure a few weeks previously of seeing the plant which had been described by Mr. Simons, but unfortunately it was not operating at the time. He thought the Institute should be congratulated on having had the full details of the plant put before it at so early a date, and he was particularly pleased that one of the youngest members of the Institute should have had the opportunity, and should have taken advantage of it, to place the particulars of the plant before the members. Mr. Roberts, in his remarks, had emphasised the importance of sintering plants and of sintering raw materials; in his own opinion sintering was becoming more important every day in the iron and steel industry.

One particular point about this plant which had impressed him very favourably was its general layout and construction. It was practically on the ground level, there was no heavy overhead structure, and there were no continuously moving parts to get out of order—an important thing in a mechanical appliance which was heated to a high temperature. Each unit was independent, and a small plant could be put down which would be very suitable for many firms who only wanted to sinter their flue-dust with the requisite quantity of ore sufficient to make a good sinter. As requirements increased, unit by unit could be added without any heavy expenditure in superstructure.

With regard to the capital cost, the cost as given to him compared most favourably with that of any of the other known sintering plants for an equivalent output. In his opinion the plant was one which should receive the very serious consideration of all ironmasters who were contemplating putting down sintering plants.

Mr. J. TORNBLAD (London) agreed with Mr. Simons that in Great Britain the sintering of fine iron ores had not received the attention that it deserved, and, further, that with a certain percentage of sinter added to the blast-furnace burden a saving of coke was obtained as well as an increased output of pig iron.

Where sinter was now used in Great Britain as part of the furnace burden the percentage of sinter was usually small. His contention and experience was, however, that where possible a much larger percentage of sinter should regularly be included in the burden, as the fuel consumption was then considerably decreased and the output of the furnace increased. A steadier and more regular working of the furnace was also the result.

In the United States, as well as in Sweden, furnaces were now working with a 100 per cent. burden of sinter, and had been doing so over long periods with most satisfactory results. With a 100 per cent. burden of sinter, available figures showed a decrease in the coke consumption of from 20 to 30 per cent., and a daily increased output of pig iron of from 25 to 40 per cent.

Comparing the new sinter plant at Cardiff with a modern Greenawalt plant, he considered the A.I.B. plant to be inefficient as well as complicated. The operating results given in Table IV. showed that with 8 pans in use, each having a grate area of about 56·75 sq. ft., or a total of 454 sq. ft., the average daily output of sinter for 5 weeks worked out at no more than 218 tons. Two medium-sized Greenawalt pans, each with a grate area of 133 sq. ft., or 266 sq. ft. for the two, would produce the same quantity of sinter and even more.

The complicated manner of handling the A.I.B. pans for tipping, recharging, and ignition, meant a loss of valuable time. With an average of 137 sintered pans per day of 24 hr., only 1 sintered pan was obtained every 10½ min., whereas in a Greenawalt plant tipping, recharging, and igniting a pan was repeatedly done in 3 min. With

12 pans eventually installed he very much doubted if, with the one crane, the time mentioned could be essentially improved upon.

Coming back to the figures in Table IV., the amount of return fines, an average of 59.3 tons per day, was excessive; that meant that the pans produced 78.6 per cent. of sinter and 21.4 per cent. of return fines. He considered that to be a very moderate result indeed, but it was explained by the small size of the pans. It was well known that, by the cooling effect of the steel sides of a sintering pan, the outer edge of the sinter in the pan was always rather soft and contained a good proportion of fines. In the 8 A.I.B. pans described the total surface area of the perimeter of the pans was 204 sq. ft., whereas for 2 Greenawalt pans with the same capacity of finished sinter the combined surface area of the sides of the pans only amounted to 73 sq. ft.

With regard to the construction, the A.I.B. pans must be as light as possible on account of their having to be moved about by an overhead crane with a considerable span; there was thus a danger of breakage.

Also, the grates in the pans were of the stationary type, so that, as Mr. Simons said, there was always the risk of the sinter sticking to the grates, should the mixture that was sintered not be exactly right. Those drawbacks were entirely eliminated in the Greenawalt pans. Being stationary, the Greenawalt pan could be made very strong, and the rotating grate bars—another feature—entirely eliminated the danger of the sinter sticking to the grates when the pans were tipped.

The system of charging the pans as practised in the A.I.B. plant at Cardiff was also far from ideal. To obtain the best results it was essential that the charge in a sintering pan should be as uniform, loose, and fluffy as possible. That could not, however, be obtained with the charging arrangement described. When the gates of the charging bunker were opened, the whole pressure of the weight of the material in the bunker bore down upon the charge being deposited in the pan beneath the bunker; consequently, at the commencement of filling the pan, when the bunker was full, the pressure upon the charge was greater than at the end when there was less material in the bunker. That irregularity was also entirely eliminated in the Greenawalt charging car, from which the materials were fed into the pan by means of rollers; the charge was thus evenly, uniformly, and lightly spread over the whole pan from one end to the other.

In his (Mr. Tornblad's) opinion, the A.I.B. ignition apparatus was not ideal. Mr. Simons stated that anthracite duff or coke breeze had to be thrown over the pan to facilitate the ignition, but that was not necessary with the Greenawalt ignition hood. He also doubted whether the A.I.B. ignition apparatus could be successfully adapted for gas ignition at plants where gas was available. Ignition with gas—either blast-furnace or coke-oven gas—was most satisfactorily accomplished with the Greenawalt gas ignition hood, and it was usually cheaper to ignite with gas than with oil.

The proprietors of the A.I.B. system claimed that the main advantage of their system over the Greenawalt system was the entire elimination of dust from the plant, as the A.I.B. pans were tipped outside the plant proper. That might be true, but he felt sure that at the tippler gear shown in Fig. 7, which was open and exposed to all winds, there would be clouds of dust when the pans were tipped. It was quite true that at the older Greenawalt plants, especially in Great Britain, where no provisions were made for dealing with the dust when the pans were tipped, dust was more or less a nuisance. In the latest Greenawalt plants, however, special hoods and dust extraction fans were incorporated in the plants, with most satisfactory results.

He (Mr. Tornblad) recently had occasion to inspect one of those modern Greenawalt plants now in operation at a works on the Continent, and he found that when the pans were tipped all the dust that then arose was entirely confined to the dust hood covering the pan and the dust-tight hopper below, which was connected to the ventilator.

In the tables Mr. Simons gave no indications as to the sintering costs, &c., for the new plant at Cardiff. For comparison with other sintering systems it would be very interesting if such costs and other data, such as the number of men employed at the plant, the electric power consumption per ton of finished sinter, repairs and maintenance, cost of the plant, and so on, were also available.

Mr. SIMONS, in reply, first wished to thank Mr. Roberts and Mr. Harbord for their very kind remarks. In reply to Mr. Barreiro he could say that there was a great future for sintering in Spain. The spathic and Obregon ores, which were used at Cardiff, were both obtained from the Bilbao district. Increasing quantities of spathic ores were being used, and it might be of commercial advantage for mine-owners in that district to convert their fine material into the form of sinter and export it, as was being done in Sweden.

In comparing any system of sintering, the three essential factors to be considered were the quality of the sinter, the capital cost of the plant, and the working costs. In these respects the A.I.B. system compared most favourably with any other system, and that was an answer to all criticisms. The efficiency of a sinter plant was not measured by the output per unit area of grate. Although two medium-sized Greenawalt pans might produce as much as eight A.I.B. pans, the building for the former would be much more costly and elaborate than that for the latter. In an A.I.B. plant there was one simple tipping arrangement, whereas in a Greenawalt plant every pan was fitted with an elaborate mechanical device. One crane could easily deal with twelve pans, and no time was lost on account of insufficient crane power.

With regard to the amount of fines produced, about 15 per cent. of flue-dust was used, and that material caused more fines to be made than if iron ore were sintered alone. Before tipping the fines into the

railway wagons they were well watered, so that the amount of fines actually made was not so much as was shown in the results published. The method of dealing with the return fines in a Greenawalt plant was very unsatisfactory. By making the sinter bed in the pan $12\frac{7}{8}$ in. deep it was possible to obtain good lumpy sinter.

With regard to the construction of the pans, it was absurd to say that they had to be as light as possible because they were moved by an overhead crane. On the same grounds one might as well say that a teeming ladle had to be made as light as possible.

Sticking was a trouble that was experienced with all types of sintering plants if there was too much carbon in the sinter mixture. The density of the material in the pans had been found to be uniform throughout by means of the segment filling gate attached to the bunker; it was shown by the regular quality of the sinter produced.

It was not absolutely necessary to use anthracite duff or coke breeze to help the ignition, but their use considerably reduced the amount of fines made. Compressed air was applied to the ignition apparatus, and there was no reason why compressed blast-furnace or coke-oven gas could not also be used. No inconvenience to the operatives has been caused by the dust during the tipping of the pans.

On behalf of the Allmänna Ingeniörsbyrå, Mr. Simons added that Mr. Tornblad had stated as evidence of the superiority of the Greenawalt system that 2 Greenawalt pans with a total grate area of 266 sq. ft. should be able to deliver as many tons of sinter per 24 hr. as the 8 pans with a total area of 454 sq. ft. produced at the A.I.B. plant in Cardiff. It was well known, however, that when sintering easily sintered raw materials rich in iron, it was possible to obtain with the same pan area and the same sintering system, up to about 100 per cent. more sinter than when raw materials which were more difficult to sinter and less rich in iron were used for the charges. As Mr. Tornblad gave no details concerning the raw materials treated in the Greenawalt pans in question, it was evident, for that very reason, that his comparative figures were of no real value for judging the efficiency of the different systems.

The production figures from several Greenawalt plants in Sweden and Norway, where pans with an area of 84 and 96 sq. ft. were used, showed a sinter production per unit area of the pans amounting to only about 55 per cent. of the output which Mr. Tornblad now said was normal for similar pans with an area of 135 sq. ft. The Greenawalt plants mentioned, in which concentrates containing 60 to 68 per cent. of iron were treated, delivered an output per unit area about 20 per cent. lower than that of the A.I.B. plant in Oskarshamn, Sweden, where purple ore with about 56 per cent. of iron was sintered in pans having an area of only $35\cdot6$ sq. ft. Those figures showed clearly that Mr. Tornblad's simple method of comparison was inconclusive.

It was not only the character of the raw materials and the sinter production which were decisive for a reliable comparison between the

different systems. The size, character and hardness of the sinter, as well as the different opinions in different works as to the size of the product—what might be counted as sinter and what as fines—were factors which affected in a high degree the estimation in question.

The amount of return fines depended very much upon how they were separated. In Cardiff, the charge was tipped over a screen with $\frac{3}{4}$ -in. openings between the bars, so that while separating the fines, sinter for bedding material was also obtained. In that way a coarser sinter was obtained for the blast-furnaces, but at the same time the percentage of fines became higher and the production of sinter lower than if, as was mostly done, a finer screen had been used and some other material than sinter had been taken for bedding material.

The managers of the plant in Cardiff had found it most appropriate to use sinter for bedding, and they had been able to do so just because of the efficiency of the sintering system; an output higher (about 20 per cent.) than that calculated could be obtained without including so high a percentage of smalls in the sinter for the blast-furnaces as had to be done with many other sintering plants. At the Greenawalt plants in Europe, the separation of the fines was generally done through a screen with $\frac{1}{4}$ to $\frac{5}{16}$ -in. openings between the bars; those screens were, however, often ineffective, so that a comparatively large amount of return fines was included in the sinter. Nevertheless the percentage of fines at the Greenawalt plants became high, and the statement had been made that at a certain large plant of that type the percentage of fines amounted to about 35 per cent. of the output.

Mr. Tornblad thought that the A.I.B. system of tipping, recharging and ignition involved a loss of valuable time, and he alleged as a reason for that opinion that the number of pans tipped per 24 hr. gave an average time of 10·5 min. between each pan, while the same operations according to the Greenawalt system took only 3 min. That comparison also was not correct, for several reasons. The calculated average time for the exchange of the pans depended upon the number of pans, and was reduced as soon as that number was increased. At the A.I.B. plant the operations mentioned were done independently of each other, so that one pan might be charged while another was transported and tipped and a third was ignited. The time for the exchange of the pans could, therefore, be reduced to 4 to 6 min., depending upon the size of the pans and the design of the plant.

The operating time of 3 min. mentioned for a Greenawalt pan seemed to be exceptionally short for ordinary running, when the ignition alone of the large pans could take about the same time. Moreover, that time must be considered in conjunction with the time necessary for the removal of dust and the handling of the covering hood. When the pans were exchanged at Cardiff, only one-eighth of the plant was withdrawn from the sintering work proper, while at a Greenawalt plant with, for instance, 2 large pans, half of the plant was withdrawn from the sintering work during the corresponding operations; at a

Dwight-Lloyd plant there was always only about one-half of the pan area in position for sintering.

With the A.I.B. system the stationary pan grates were easily accessible for cleaning, and the cleaning as well as the exchange of the grates could be carried out without any loss of time by putting in a spare pan when necessary. The cleaning and exchange of the grates of large Greenawalt pans could not be done without interrupting the working. In the later Greenawalt plants movable grates were used in order to reduce at least the loss of time on cleaning, but that was not without disadvantages. The difficulty lay in getting the large number of movable grate bars to operate; in one case, for instance, that difficulty had caused the movable grates to be exchanged at once for stationary ones. The simple, stationary grates of the A.I.B. system were therefore much to be preferred.

Mr. Tornblad's misgivings as to the excessive pressure upon the charge when charging had not been borne out. By a suitable construction and arrangement of the charging bin the pressure could be regulated according to the character of the raw material.

The open ignition apparatus used with the A.I.B. system had the great advantage over the closed hood that the charge was quickly ignited all over. It could, where necessary, be constructed for ignition with gas.

Mr. Tornblad thought that the use of an overhead crane for the transport of the pans involved a danger of breakage. Practice proved the contrary; such a crane had now been in operation for nearly three years at the A.I.B. plant in Oskarshamn without any accident or breakage having occurred.

This paper was also presented at the Additional Meeting held at Glasgow on May 9, 1929.

Mr. MANN (Glasgow) asked if any attempt had been made to make the process continuous by sintering on a continuous conveyor instead of in pans. He could foresee difficulty there in getting sufficient heat for the initial firing of the charge, but he thought that perhaps the attempt had been made.

The CHAIRMAN (Mr. R. Hamilton) referred to the last paragraph on p. 89: "The result of separating out the fine ores by screening and sintering at the Cardiff Works has been the attainment of a consistently higher output, and coke consumption has been reduced by about 1 cwt., the amount of sinter used varying from 16 to 25 per cent. of the ore burden. In addition to separating out the fines, the lumpy ore and limestone are crushed to a uniform size." It had occurred to him on reading that passage that some of the saving might have been due

to the preparation and crushing of the ores and limestone to a uniform size. He could see that if the sintering were just an adjunct the thing of real importance was the preparation of the materials to a uniform size, and it might possibly be said that the saving was not really due to the sintering but to the preparing of the materials.

Mr. SIMONS replied that the ore-crushing plant had been installed in Cardiff for some years, and the crushing of the ores and limestone had considerably helped to increase the make of the blast-furnaces. Previous to the erection of the sinter plant the fines went into the blast-furnace together with the rough ore. It was not until the fines were screened out and sintered that the results mentioned were obtained.

CORRESPONDENCE.

Mr. H. J. BUSH (London) wrote: The description of the A.I.B. sintering plant at Cardiff is strangely reminiscent of the accounts published some eighteen to twenty years ago of the sintering of fine iron ores in Huntington-Heberlein pots or converters. On comparing the Cardiff pots with installations erected many years ago on the Continent and in America, one finds much the same basic design so far as the pots are concerned, and the manner of lifting each pot with its charge and dumping it outside the building. Both the downward and upward draught were practised in the Huntington-Heberlein pots, and grids of many shapes and sizes were used. The method of charging the pot and igniting, adapted from the Greenawalt system, is certainly an improvement, but there still remain the numerous and intermittent manipulations of the small pot, with the attendant high labour and maintenance costs.

With the advent of the straight-line continuously working Dwight-Lloyd machine, the sintering of iron ore in small unit pots fell into disuse, and it is a little difficult to appreciate where the advantage lies in the "new" A.I.B. system used at Cardiff, especially as no figures are forthcoming concerning either the capital cost or the working costs.

It takes eight A.I.B. pots, with a total of 450 sq. ft. of grate area, to turn out 218 tons of sinter in 24 hr., and the ground-space occupied is approximately 69 ft. by 38 ft. A Dwight-Lloyd machine would do the same tonnage on 140 sq. ft. of grate area, and would not occupy more space. The machine would be a single unit requiring three men in attendance, the power consumption would be 15 to 16 kw.-hr. per ton of sinter, and, above all, the operation would be continuous, with a resultant uniformity of product. Neither would it be necessary to side-step the dust nuisance by excursions into the yard.

The path of progress in the sintering of fine ores will not, in the opinion of the writer, be found to lie in a multiplicity of small units, but rather in large units working on a continuous system; though whether such units in Great Britain will ever reach the outputs of the largest Continental machines making 800 tons of sinter per machine per day, is perhaps debatable, unless sintering is undertaken on a more or less co-operative basis at suitably selected distributing centres.

It would have added to the interest of the paper if the author had given a little more information concerning actual expenditure per ton of sinter in man-hours, upkeep, and power.

Mr. SIMONS wrote in reply: The pan filling arrangement of the A.I.B. sinter plant is not copied from the Greenawalt system. A continuous system of sintering makes inferior sinter to that made in a stationary pan. Some years ago a sinter plant working on a continuous system was installed at Cardiff, but it was most unsatisfactory. The cost was excessive, the sinter made was of very poor quality, and the plant was eventually scrapped, an A.I.B. plant being installed.

Whether large or small sinter plant units are built is entirely a question of economics, and is irrelevant to the merits of the different systems of sintering. Some very large A.I.B. plants have been and are at present being built. Consequently if large centralised sinter plants were built there is no reason why the A.I.B. system could not be adopted.

Mr. Bush thinks that the path of progress in sintering will be found to lie in large units working on a continuous system, and recommends, therefore, large co-operative plants. This may seem a desirable development, but it is unfortunately not so easy to attain. The first reason is that by no means all raw materials can be sintered to advantage in the continuously working sintering machines used up to now. The principal difficulty of the continuously working systems is that it is difficult to effect a practical and economical regulation of the vacuum and of the air volume for several pans coupled to the same fan when they are in different stages of sintering. When difficultly sintered raw materials are treated, the percentage of fines and the consumption of fuel, therefore, become high, and also the sinter often becomes very fine-grained.

In a screening test made in Germany, with sinter sent in railway wagons direct from a large Dwight-Lloyd plant to the blast-furnace, the sinter was found to have the following sizes:

Above 10 mm.	%
Between 10 and 5 mm.	27·8
Between 5 and 1 mm.	32·5
Below 1 mm.	30·8
	8·9

In another screening test, also made in Germany, with sinter which

had been exported to Germany from the A.I.B. plant at Oskarshamn, Sweden, the following considerably better results were obtained :

	%
Above 12 mm.	64.00
Between 12 and 1 mm.	32.55
Below 1 mm.	3.45

The last-mentioned sinter had been reloaded three times by means of a grab before being screened.

In both cases the raw material was purple ore of about the same character. The cost of production per ton of sinter is lower for the Swedish sinter, even though the A.I.B. plant mentioned uses 8 sintering pans with a diameter of only 6 ft. 7 in. and produces 154 tons per 24 hr., whilst the Dwight-Lloyd plant in question produces about 600 tons per 24 hr. Even if these figures cannot be taken as a standard when comparing these two systems, they show clearly enough that when comparing different systems the quality of the sinter must not be overlooked. On account of the high installation costs the Dwight-Lloyd plants must be built for a comparatively large output in order to be economical.

Although it has not long been on the market, the A.I.B. system has already been employed for three plants, one of which is for a production of 600 tons per 24 hr. ; in addition, three more plants are now being built, and will be started within the next months. With pans 8 to 10 ft. in diam. the system can be used for very large plants.

THE EROSION OF GUNS.*

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SUMMARY.

Owing to the extreme severity of the conditions to which the bore of a gun is exposed, some material is removed from its surface at each round. Erosion steadily enlarges the front slope of the chamber and the bore forward of that position, the effect being a maximum near the commencement of rifling, diminishing through the first three or four calibres of the rifling and becoming unimportant as the muzzle of the gun is reached. At any position, the material of the lands is removed about twice as fast as that of the grooves. Characteristics of the bore of a fired gun include a hardened (martensitic) skin due to heating of the surface layer followed by very rapid cooling by conduction, and a network of surface cracks due to stresses set up by the alternate heating and cooling. These effects, however, do not appear to be determinant factors in erosion, which is due to the melting and washing away of a thin surface layer at each round by the sweep of highly heated gas following the projectile. Erosion increases with increasing calorific value of the propellant, and with increasing pressure and velocity of the gas. Thus, although the erosion is most intense near the commencement of rifling, it must have occurred when the projectile had travelled beyond that position. Simple gas erosion, such as occurs in erosion vents, is accordingly regarded as the main factor in the wear of big guns. Erosion vent experiments show the relative erodibility of different steels and non-ferrous metals, and illustrate the paramount importance of the melting point, though other properties, such as latent heat of fusion and thermal conductivity, exercise some influence. Pure iron is slightly less erodible than any steel. The relative erosive power of different propellants is dependent on their calorific values; a reduction in calorific value of 25 per cent. below that of cordite M.D. approximately halves the amount of erosion as measured by erosion vent experiments.

* Communication from the Research Department, Woolwich, received November 23, 1928.

Frictional wear by the projectile is a factor which must be taken into account in considering the life of a gun. Its effect is greatest in small arms; it is of some consequence also in guns of small and medium calibre, but it rapidly diminishes in importance, in proportion to erosion by gas action only, as the calibre increases.

Scoring (if it occurs) begins later in the life of a gun, and is rapid, irregular, and highly localised. After general erosion, or some abnormal expansion, has produced a certain enlargement of the bore, scoring may set in as a result of the escape of gas past the driving band—the grooves, in this instance, being first attacked and the effect spreading laterally to the lands. It is somewhat rare in big guns, but more frequent in small and medium calibre guns, especially in quick-firing guns firing fixed ammunition, in which efficient obturation by the driving band cannot be secured by ramming.

The more uniform erosion, which precedes scoring in small guns and which is characteristic of big guns throughout their life, is due to the melting and sweeping forward of a thin layer of the bore surface. For this there is no metallurgical remedy. The use of a cooler propellant and a careful design of the chamber afford the only practicable means of reducing erosion.

GUN erosion has been studied by a large number of investigators, prominent among whom have been Noble and Abel in England, Hugoniot and Vieille in France, and Tschernoff in Russia. Reference to their work is made in the bibliography appended to this paper. The problem has been approached from many directions—by the chemist interested in propellants, by the metallurgist dealing with the materials of construction of the gun, and by the ballistician who is concerned with its accuracy and efficiency as a weapon. In the present paper the metallurgical aspect of the question is considered.

EXAMINATION OF WORN GUNS.

Erosion is a general term applied to the removal of metal from the bore of a gun by the action of the propellant gases. The mechanism of erosion was investigated in the Research Department, Woolwich, many years ago, mainly by Captain (now Colonel) H. G. Howorth, R.A.,⁽¹⁴⁾ in 1910. Examination of guns worn out in service has been continued from time to time since his Report was issued.

An examination of the bore of any gun which has fired

modern smokeless propellants reveals two characteristics of the surface :

- (1) A very hard thin skin.
- (2) A network of surface cracks a few hundredths of an inch in depth.

Character of the Hardened Skin.

In sections cut normally to the surface of the bore, the hardened skin is usually shown under the microscope as a white band, which on deeper etching reveals the structure of martensite (Figs. 1 to 7, Plates VI. to VIII.). It increases in thickness from muzzle to commencement of rifling, and continues through the chamber. At any given point along the gun the skin is usually thickest at the top of the driving edge of the land. The larger the calibre of the gun, the thicker is the hardened skin at corresponding positions.

The approximate average depths of hardened skins, observed in guns of various calibres which have fired cordite M.D., are :

Calibre.	At Commencement of Rifling.	At Muzzle.
	In.	In.
16-in.	0·016	0·006
15-in.	0·011	0·004
12-in.	0·009	0·003
6-in.	0·005	0·001
3·3-in. (18-pdr.)	0·0025	Trace
0·303-in. rifle	0·0008	Trace

A hardened skin is also found on steel crusher gauges (Figs. 8 and 9, Plate VIII.), on the base of proof shot or shell of large calibre (Figs. 10 to 13, Plates VIII. and IX.), and in fact on any steel surface on which the propellant gas has acted for a sufficient time. The presence and depth of the hardened skin produced by contact with propellant gases depend not only on the time of contact of the steel with the gas, but also largely on the speed of flow of the gas over the surface. The more rapid the stream of gas, the more heat can be supplied to the steel in a given time. The presence of a hardened skin may thus be a useful indication of the action of gas, though its absence is not proof of absence of gas action. It should be noted, moreover, that a similar skin can be produced

by friction unaided by gas-washing, as in groove marks on fired projectiles, at the corners of the ribs of rifled shell (Fig. 14), and on the surfaces of steel rails,* of heavily braked railway tyres,† of wire rope subject to friction on a pulley,‡ and of ball-bearings which have been allowed to run dry.

The thickening of the hardened skin on the driving edge of the lands is caused by additional heating due to friction at this position.

The conditions producing a hardened skin of the type found in guns are an extremely rapid and short heating of the surface of the steel to a temperature well above the critical range. The structural change in the steel is due to solution of carbide in the iron throughout a layer near the surface which reaches a sufficiently high temperature, and the subsequent rapid cooling of this layer by conduction of heat to the cold steel beneath. By striking a momentary arc from a steel pencil on to the surface of a block of steel, a small saucer-shaped patch of skin is produced (Fig. 15), which is precisely similar to the skin formed in the inner tube of a gun.

The formation and character of the hardened skin were studied by placing cylinders of a 0·8 per cent. carbon steel in the chamber of a 15-in. gun during firing. In this steel, which consists almost wholly of pearlite, the mutual solution of ferrite and cementite is more rapid than in steels with a ferrite network. Cylinders were examined after 1, 5, and 10 rounds (Figs. 17 to 19, Plate X.). The maximum thickness of hardened skin after 1 round was 0·0037 in., after 5 rounds 0·0114 in., and after 10 rounds 0·0118 in. The skin thus attains practically its full depth before 5 rounds have been fired. It consists of coarse martensite at the outside, followed by fine martensite, troostite, ferrite and troostite, then passing through a narrow sorbitic region to the original structure of the steel (Fig. 20). The maximum Brinell hardness, measured

* A hardened skin was found on the St. Neots rail (see Board of Trade Report on "The Loss of Strength in Steel Rails through Use in Railways," 1900). Micrographs of this skin were published by J. E. Stead, *Proceedings of the Institution of Mechanical Engineers*, 1899, p. 77, and by W. H. Merrett, *ibid.*, 1904, p. 140. Several illustrations of the hardened skin on steel rails have appeared; a recent example is contained in a paper on "The Investigation of Failures," by J. W. Bampfylde, *Journal of the Photomicrographic Society*, 1927, vol. xiv. p. 23.

† H. Brearley, *Metallurgist*, 1925, vol. i. p. 132.

‡ E. A. Atkins, *Journal of the Iron and Steel Institute*, 1927, No. I. p. 443, Fig. 45.

with a 1-mm. ball and 30-kg. load, was 547, the hardness of the original steel being 209.

Character of the Network of Fissures.

The surface of the bore of a gun at an early stage in its life becomes covered with a network of fissures. In the chamber the network is fairly uniform, in the rifled portion the more pronounced cracks are longitudinal in the grooves and transverse on the lands (Figs. 21 and 22, Plates XI. and XII.). The deepest crack is usually that which runs longitudinally in the driving angle of the groove.

Consideration has been given to the causes of the cracking of the skin by Tschernoff,⁽³²⁾ Okochi,⁽²³⁾ and others, who expressed the opinion that it is due to the thermal contraction and critical volume changes which occur on cooling. These volume changes give rise to a network of cracks such as are found in the chamber. In the grooves the longitudinal cracks are rendered more prominent by the forward motion of the gases. On the lands, where some relief of stress can occur laterally, but not longitudinally, the transverse cracks predominate.

According to this theory, a hardened skin is necessary to the formation of fissures, but later experiments show that surface cracking of an intercrystalline character may occur under the action of the hot gases in metals which will not harden on quenching. There is no reason to suppose that the elimination of the formation of a hardened skin would prevent surface cracking or diminish erosion.

Examination of surface cracking is facilitated by pickling the sectioned gun tube in 20 per cent. sulphuric acid at about 80° C. This treatment exaggerates the size of the cracks, but reveals their character and arrangement very clearly (Figs. 23 and 26, Plates XIII. and XIV.). The appearance of the surface of the bore of a worn 15-in. gun at one calibre forward of the commencement of rifling is shown in Fig. 30 (Plate XVI.).

Rate of Removal of Steel by Erosion.

The characteristic appearances described above are accompaniments of erosion. The actual surface of the bore exposed to

the propellant gases is constantly changing as erosion proceeds, and is different at every round. Erosion steadily enlarges the front slope of the chamber and the bore forward of that position. The maximum erosion occurs at the commencement of rifling, and diminishes in the direction of the muzzle. Measurements made on 6-in., 9·2-in., and 12-in. guns indicate that loss of material from the lands occurs at about twice the rate as from the grooves.

The life of a gun is determined by the depth of steel which may be removed before the gun becomes too inaccurate to use. It is sometimes still further shortened by the occurrence of severe localised erosion or "scoring." Scoring, however, is comparatively rare in well-designed high-power guns; it is most pronounced in small quick-firing guns firing fixed ammunition.

Scoring.

Scoring is the irregular eating away of the surface of the bore in holes and gutters (Figs. 24 to 26, Plates XIII. and XIV.). It is, as a rule, confined to the first few calibres length of the bore forward of the commencement of rifling. Maximum scoring occurs at about 6 in. forward of the commencement of rifling in 18-pdr. guns, and at about 1 ft. forward of the commencement of rifling in 6-in. guns.

It may be due in part to the motion of the gas behind the projectile—that is, to currents in the propellant gases set up by their passage from the chamber to the bore, with accompanying reduction of the cross-sectional area of the stream. This would explain the position of maximum scoring, but would not satisfactorily account for the fact that maximum scoring is almost invariably at the "up" position*; nor would it account for the fact that in many instances the lands are well preserved after the scoring in the grooves has become very marked (Fig. 27, Plate XIV.). It seems probable, therefore, that scoring begins (if it occurs at all) after some general enlargement of the bore has already taken place, and is due, at least in part, to gas-washing produced by

* P. Charbonnier⁽⁶⁾ (*loc. cit.*, p. 114) states that the position of the charge in the lower part of the chamber sufficiently explains the relative protection of the lower part of the bore compared with the upper parts; but this ceases to apply when the diameter of the chamber approximates to that of the bore.

the escape of propellant gases past the driving band during the initial stages of motion of the projectile.

Escape of Gas through Holes Drilled in the Shot.—It has been suggested by Vieille⁽³⁵⁾ that not only is scoring due to escape of gas past the driving band, but that normal erosion is also due to such escape through the minute channels existing in the cracked surface layer. It is a matter of importance to determine the minimum size of orifice through which gas can pass without undergoing sufficient cooling to render it inactive as an erosive agent. Two 18-pdr. proof shot were drilled longitudinally, one with a central axial hole 0·5 in. in diam., and the other with four holes each 0·25 in. in diam., spaced symmetrically relative to the axis of the shot and to each other. The two shot were then fired under the normal conditions adopted for solid 18-pdr. proof shot, with the following results :

18-pdr. Proof Shot.	Weight of Projectile.	Muzzle Velocity. Ft. per sec.	Maximum Pressure. Tons per sq. in.
	Lb. oz.		
Solid	18 8	1677	13·65
Drilled with hole 0·5 in. in diam. .	18 1½	1602	12·35
Drilled with 4 holes 0·25 in. in diam. .	18 1½	1607	12·65

There was thus a decrease in recorded pressures and muzzle velocities relative to those obtained for solid shot.

The fired shot were sectioned. Microscopical examination of the metal in the neighbourhood of the holes showed the presence of a hardened, slowly etching surface layer. The structure at a position near the nose of the shot drilled with four holes is shown in Fig. 16 (Plate IX.). The depth of this hardened skin appeared to be constant throughout the length of the shot, and was 0·0034 in. for each shot. Brinell hardness measurements made with a 1-mm. ball and 30-kg. load on the bore surface of the drilled holes gave 341 in comparison with 220, the normal hardness of the material of the proof shot.

The presence and character of this hardened skin are conclusive evidence that propellant gases had issued through the drilled hole during the firing of these shot.

It was thought desirable to employ a smaller orifice, but a

hole much less than 0·25 in. in diam. could not be bored through the full length of a proof shot. Two 18-pdr. proof shot were therefore drilled with axial holes 0·5 in. in diam. The forward end of these holes was then fitted with a plug of annealed 0·8 per cent. carbon steel. This steel (the same type as was used for the cylinders subjected to chamber conditions during firing) was chosen because it is sensitive to the formation of a hardened skin and has poor resistance to erosion. The plug in one shot was drilled with an axial hole 2 mm. in diam., while the other was drilled longitudinally with 4 holes each 2 mm. in diam. :

18-pdr. Proof Shot.	Weight of Projectile.	Muzzle Velocity. Ft. per sec.	Maximum Pressure. Tons per sq. in.
	Lb. oz.		
Solid shot	18 8	1672	13·40
Shot fitted with plug with 1 hole, 2 mm. in diam.	18 4	1668	13·35
Shot fitted with plug with 4 holes, 2 mm. in diam.	18 3½	1659	13·45

There was thus no diminution in maximum pressure, and only a slight loss in muzzle velocity.

The plugs were weighed before and after the proof shot had been fired ; the loss of weight on firing was 0·180 gm. for the plug containing one hole, and 0·233 gm. for that with 4 holes. As the plugs suffered some slight abrasion in the sand bay, these figures may be rather too high, but evidence of the passage of propellant gases through the plugs was afforded by the fact that along all the holes there was a slowly etching hardened layer, which appeared to be of a constant depth of 0·0022 in. throughout the length of the plugs.

Escape of Gas past the Driving Band.—In order to ascertain whether there had been any escape of gas past the driving band, the surface of the shot was examined by etching, but there was no trace of a hardened skin due to gas-washing. Thus, these experiments, while they show that gas passes through a 2-mm. orifice in the proof shot at some time during its passage down the bore, fail to indicate (in the case of a new 18-pdr. gun, at least) that there is any escape of propellant gases past the driving band during the initial stages of motion. Some 4-in. proof shot fired

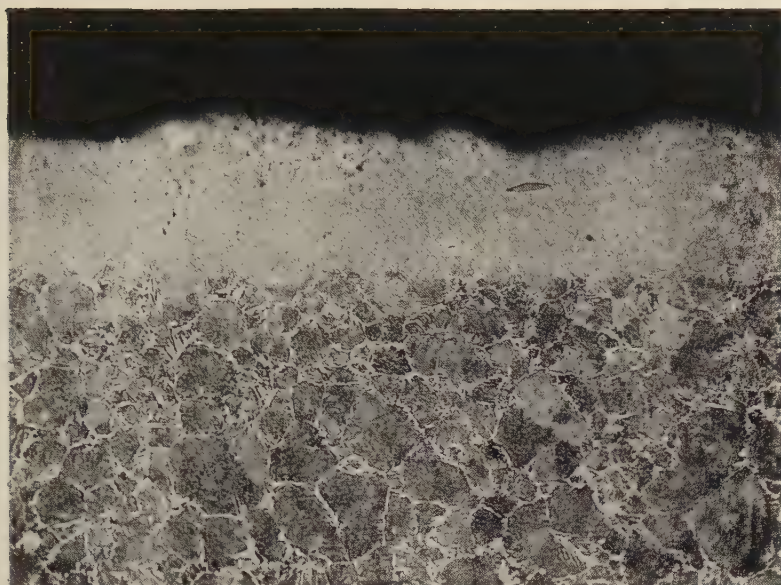


FIG. 1.—Hardened skin in 16-in. gun tube (nickel steel). $\times 100$.



FIG. 2.—Tangential to bore. $\times 1000$.

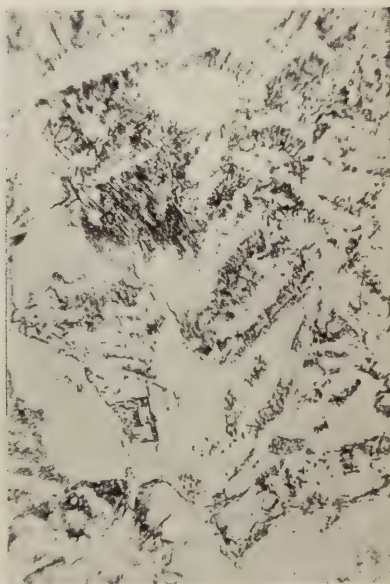


FIG. 3.—0.1 in. below surface. $\times 1000$.



FIG. 4.—On groove, showing a troostitic layer below the skin. $\times 100$.

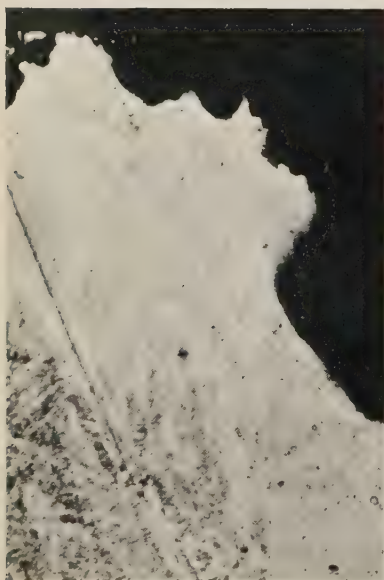


FIG. 5.—On land. $\times 100$.



FIG. 6.—Martensitic structure of the skin shown in Fig. 5. $\times 1000$.

Hardened skin in 15-in. gun tube (nickel-chromium steel) at 54 in. forward of commencement of rifling.

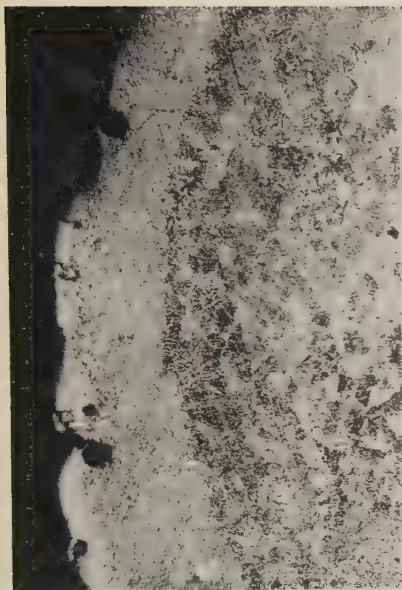


FIG. 7.—On land of 6-in. gun tube at 8.5 in. forward of commencement of rifling. $\times 100$.

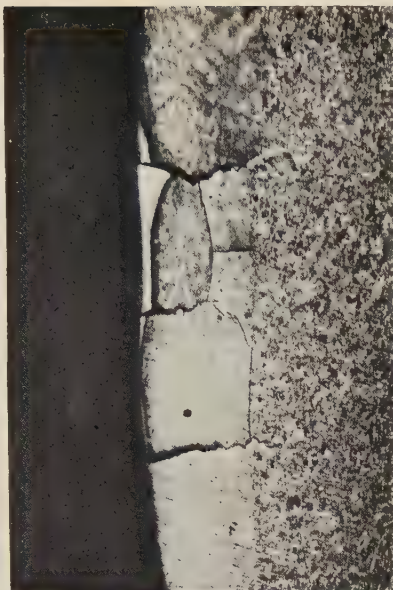


FIG. 8.—On outside of crusher gauge. $\times 25$.



FIG. 9.—On bore of crusher gauge. $\times 10$.

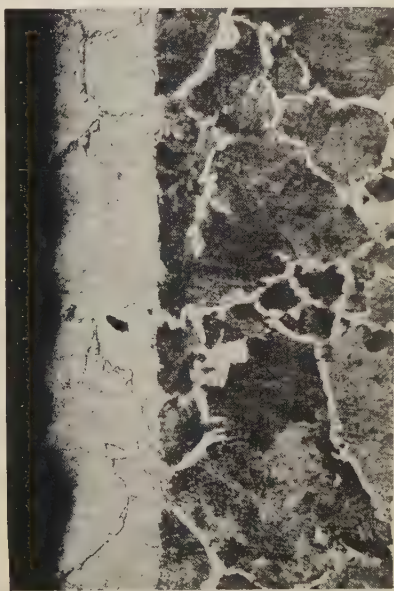


FIG. 10.—On base of 8-in. proof shot. $\times 100$.

Structure of hardened skins.



FIG. 11.—On base of 16-in. proof shot (oblique section). $\times 500$.

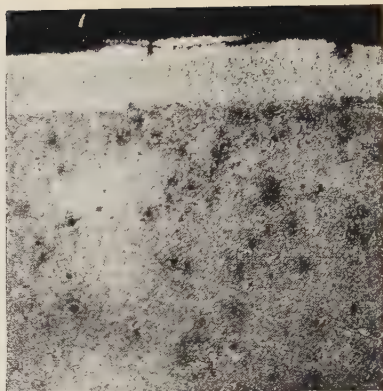


FIG. 12.—On centre of base. $\times 100$.



FIG. 13.—On side of base. $\times 100$.



FIG. 14.—On rifled portion. $\times 100$.

Figs. 12 to 14 are sections of a 210-mm. rifled shell fired from a German long-range gun.



FIG. 15.—Produced by a momentary arc. $\times 100$.

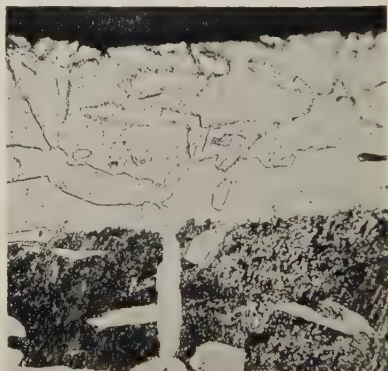


FIG. 16.—At forward end of hole drilled through 18-pdr. proof shot. $\times 250$.

Structure of hardened skins.

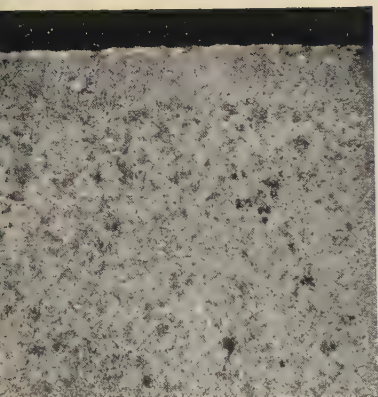


FIG. 17.—After 1 round. $\times 100$.



FIG. 18.—After 5 rounds. $\times 100$.

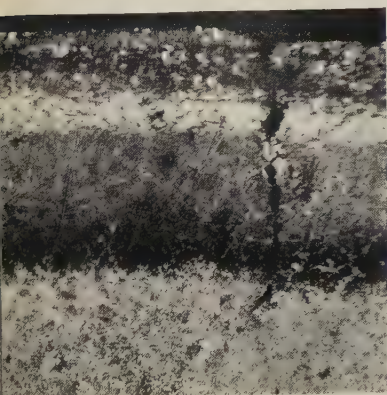


FIG. 19.—After 10 rounds. $\times 100$.



FIG. 20.—After 5 rounds. $\times 1000$.
(Reduced to four-sevenths in reproduction.)

Structure of the surface of a cylinder of 0.8 per cent. carbon steel placed in the chamber of a 15-in. gun during firing.

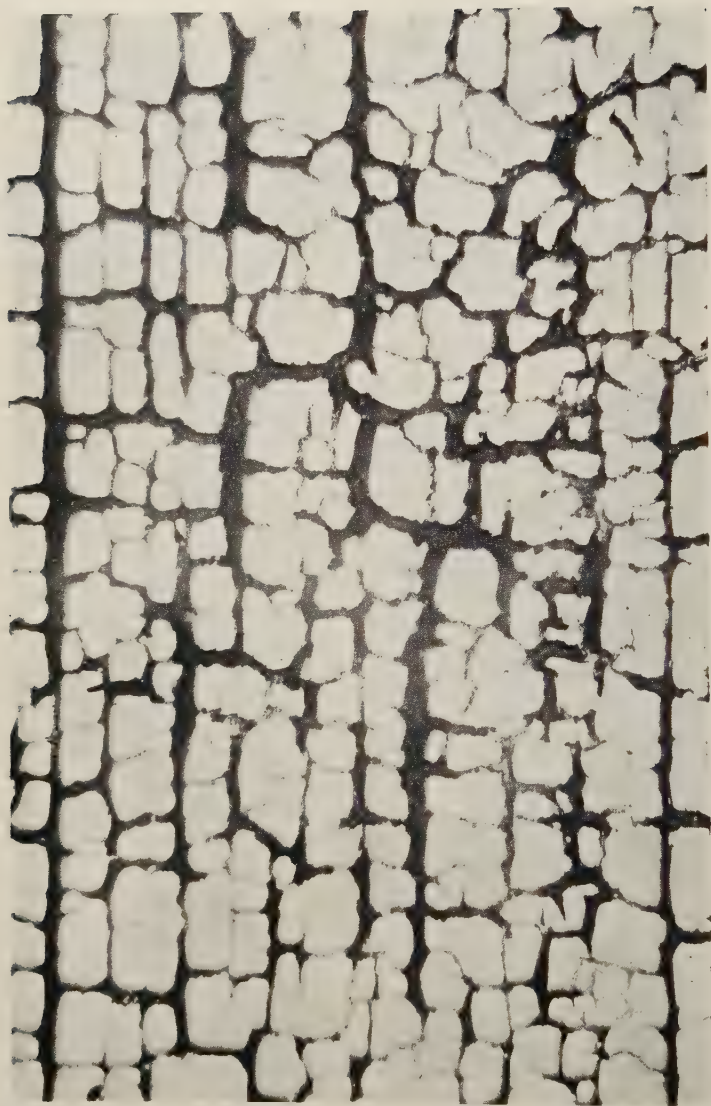


FIG. 21.—Surface cracking in the groove of a 16-in. gun at 27 ft. forward of the commencement of rifling. $\times 50$.



FIG. 22.—Surface cracking in the land of a 16-in. gun at 27 ft. forward of the commencement of rifling. $\times 50$.

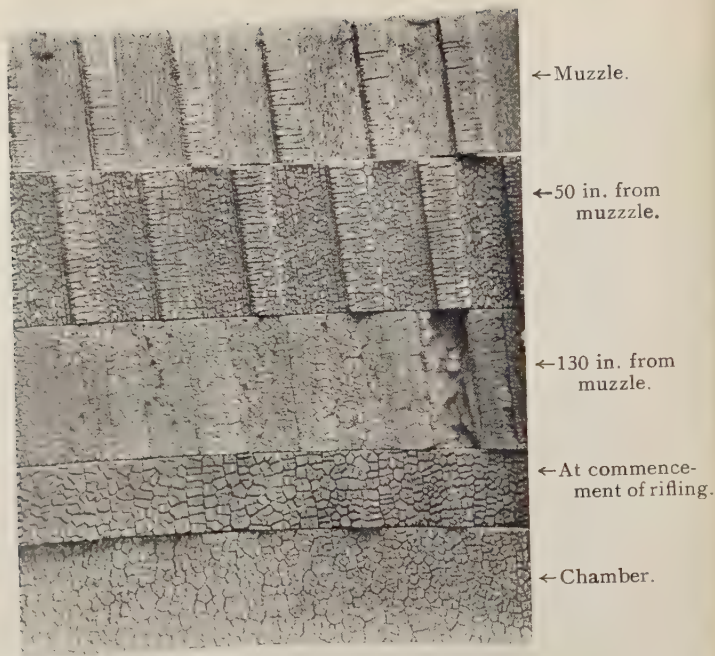


FIG. 23.—Sections from 60-pdr. gun tube, pickled in 20 per cent. sulphuric acid at 80°C., showing surface cracking. (Two-thirds actual size.)

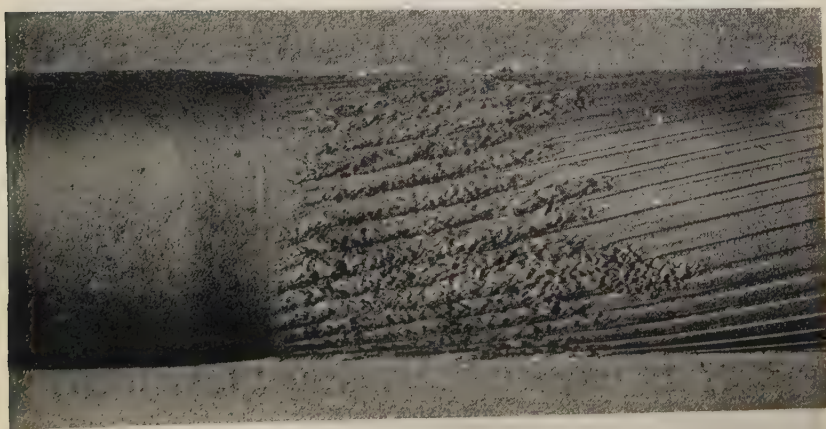


FIG. 24.—Inner tube of 6-in. howitzer (No. 2083, nickel-chromium steel) which had fired 1,846 rounds with cordite M.D., showing scoring. (One-quarter actual size.)

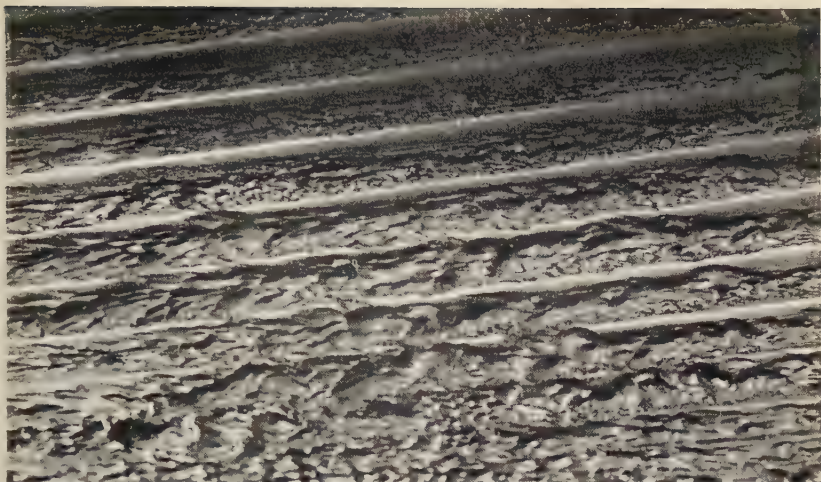


FIG. 25.—Scoring in 6-in. Mark VII. gun tube. (Two-thirds actual size.)



FIG. 26.—Section through the specimen shown in Fig. 25, after pickling in 20 per cent. sulphuric acid.

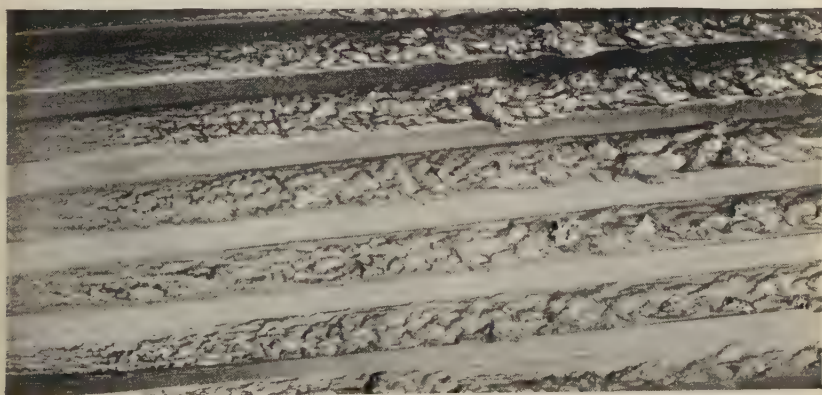


FIG. 27.—Scoring in 18-pdr. gun tube ; maximum effect 6 in. forward of commencement of rifling. (Two-thirds actual size.)



FIG. 28.—Illustration of the wedge action of copper from the driving band in enlarging a crack in a carbon steel gun tube. $\times 50$.

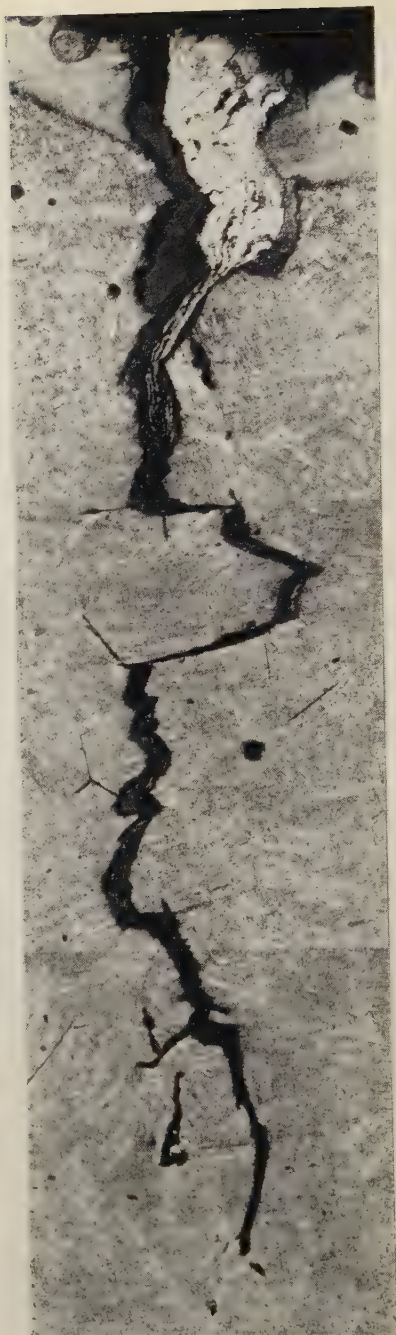


FIG. 29.—Crack in 15-in. gun tube of temper-brittle nickel-chromium steel. $\times 100$.

Cracks in gun tubes. (Reduced to four-sevenths in reproduction.)



FIG. 30.—15-in. tube near commencement of rifling. (Nickel-chromium steel.) $\times 0.6$.

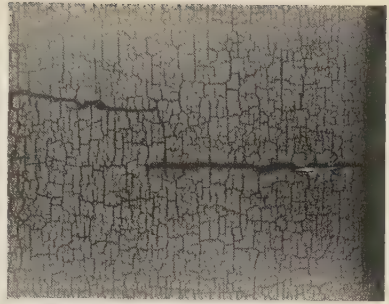


FIG. 31.—60-pdr. chamber. (Carbon steel.) $\times 0.8$.



FIG. 32.—6-in. chamber. $\times 2$.



FIG. 33.—On non-driving edge of land of 6-in. howitzer. $\times 2$.



FIG. 34.—60-pdr. chamber. $\times 2$.

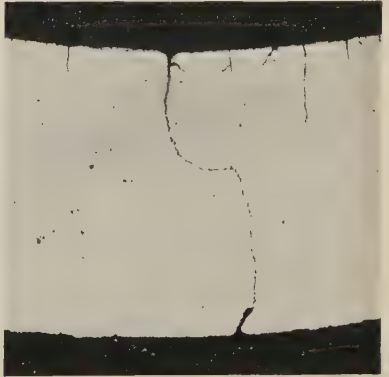


FIG. 35.— $\frac{1}{2}$ in. from section shown in Fig. 34. $\times 2$.

Cracks in gun tubes.

in a worn 4-in. Mark V* gun (mean wear at 1 in. from commencement of rifling, 0.039 in.) were examined. One of these showed a hardened skin (maximum thickness, 0.0010 in.) produced by gas-washing forward of the driving band. The driving band itself showed some signs of gas-washing. Four other shot fired in the same gun showed no hardened skin on the side of the shot. It seems, therefore, that the formation of a hardened skin, indicating gas-washing, on the projectile forward of the driving band is not a necessary consequence of the worn condition of the bore (except possibly when scoring is already very pronounced), but is fortuitous and due to occasional faulty ramming or bad centring of the projectile in the gun. In a worn quick-firing gun firing fixed ammunition, however, the same efficiency of obturation could not be obtained.

Cracked Tubes.

The examination of a number of split inner "A" tubes of 12-in. Mark VIII. guns led Howorth⁽¹⁴⁾ to the conclusion that the cracking was due to an extension of the system of surface cracks, especially those at the driving angle of the grooves, which under certain conditions might spread very rapidly in carbon gun steels. The spread of such cracks might be accelerated by the wedge action of copper derived from the driving band acting in the manner illustrated in Fig. 28 (Plate XV.). This effect has been fully described by Howe.⁽¹³⁾

Since that time several inner "A" tubes of 60-pdr. and 6-in. guns which have cracked right through have been examined (Fig. 31, Plate XVI.). Examination of the chambers of four 60-pdr. and three 6-in. guns which showed cracks penetrating through the wall at the "up" position indicated that these cracks had developed from deep longitudinal fissures in the network of surface cracks produced by firing (Figs. 32 to 35, Plate XVI.). Many small cracks penetrate the wall of the tubes by a path deviating from the normal, and adjacent cracks tend to meet. When two fissures meet in this way, a piece of steel being almost surrounded by cracks becomes loose, and is easily removed by the action of the gases. Owing to gas-washing, the cavity so produced becomes longer and deeper, but the spread of the crack

continues until it penetrates through the wall, or until the thickness of the wall of the tube becomes reduced to such an extent that it is unable to withstand the firing stresses and fracture ensues. Gases had penetrated through the open cracks of most of the tubes, and the effects of gas-washing were evident on the outside, which had been in contact with the "A" tube; but there was evidence of the cracks being completed by fracture with no signs of gas-washing, the effect of which, however, would probably have appeared at a later stage.

Every instance of cracking through the wall thickness of the chambers of guns brought to the notice of the Research Department, Woolwich, and nearly every instance of cracking in the bore, has occurred in carbon steel tubes, and the defect may therefore be regarded as a thing of the past. With the exception of one or two early examples of cracking in inner tubes of temper-brittle nickel-chromium steel, no alloy steel tube has shown this defect.

An example of a crack in a nickel-chromium steel tube with an Izod impact figure of 7 ft.-lb. is illustrated in Fig. 29 (Plate XV.); this is of interest in showing the apparently intercrystalline character of the crack in temper-brittle steel.

*Examination of Guns Worn Out with Cordite M.D.
and with N.C.T.*

Useful information has been gained by the examination of worn-out tubes from guns which had fired different propellants. The original cordite (Mark I.), consisting of 58 per cent. nitro-glycerine, 37 per cent. nitro-cellulose, and 5 per cent. mineral jelly, caused serious erosion in 4.7-in. and similar guns, and it eroded large high-velocity guns with such rapidity that the use of a cooler propellant became imperative. This led to the work of Sir Andrew Noble and others on the effect of varying the proportions of nitro-glycerine and gun-cotton, and eventually to the introduction of cordite M.D., in which the nitro-glycerine was reduced from 58 to 30 per cent.

The change from cordite Mark I. (calorific value, 1150 cal.) to cordite M.D. (950 cal.) trebled the life of big guns. Similarly the use of nitro-cellulose (810 cal.) in place of cordite M.D. leads

to increased life. In order to compare the effect of different propellants on the surface of the steel, the following worn-out guns were selected for examination :

	Number and Nature of Rounds Fired. Equivalent Full Rounds.	
	Cordite M.D.	N.C.T.
4.5-in. howitzer, No. 878	7 at proof	8832
„ „ „ No. 2342	5759	None
6-in. 26-cwt. howitzer, No. 1542 . .	7 at proof	9558
„ „ „ No. 2083	1846	None

The 4.5-in. howitzer tubes were of nickel steel, and those of the 6-in. howitzers of nickel-chromium steel. The relative lives of the two 6-in. howitzers show an abnormally high ratio in favour of N.C.T., as scoring had set in rather early in the life of howitzer No. 2083. The ratio is usually under 2.

The examination indicated that there was no characteristic difference in the type of crack produced by either propellant. The cracks in all instances were sharp at the bottom. Their maximum depth was about 0.05 in. in the tubes worn out with N.C.T., and 0.03 in. in those worn out with cordite, the apparent depth of the crack being reduced by the more rapid erosion of the surface of the tubes worn out with cordite. The latter tubes showed more local erosion and scoring, this effect being very pronounced in 6-in. howitzer No. 2083 (Fig. 24, Plate XIII.).

The character of the hardened skins and of the surface cracking was the same in each case, the difference between cordite and N.C.T. being confined to the more rapid removal of steel from the surface by cordite.

Examination of Guns Worn Out, Lubricated and Non-Lubricated.

A comparative examination was made of two 60-pdr. guns, each of which had fired about 4500 equivalent full charges of cordite M.D. One had been lubricated with wool-grease throughout the last two-thirds of its life, and the other had been worn

out dry. The main differences observed were a slightly greater maximum depth of scoring in the non-lubricated gun, and rather more coppering in the lubricated gun. The character of the surface cracking was almost identical at similar positions throughout the tubes. It appears that lubrication is without influence on the character of the hardened skin and the surface cracking which accompany erosion. Its action may be, rather, to preserve uniformity of erosion and so avoid deep scoring, though the examples examined do not lead to the conclusion that deep scoring can be eliminated by the use of lubricants. It is possible, however, that the scoring observed in the lubricated tube had commenced during the first one-third of its life before lubrication was introduced.

EROSION VENT EXPERIMENTS.

Previous Work.

Since the action of the hot gases from the propellant is the principal factor governing the extent of erosion, it is natural that their effect should long ago have been studied by measurements of loss of weight of vents through which the hot products of combustion of the propellant had been passed. Such experiments were made by Sir Andrew Noble in 1882-85, and since then by many other investigators.* The 1885 experiments were carried out with black powder only. Sir Andrew Noble concluded that the milder the steel the less the erosion. To confirm this, the Superintendent of the Royal Gun Factory, Woolwich,⁽¹⁾ employed a 4-in. gun bored out and fitted with erosion tubes of steels containing from 0.16 to 1.14 per cent. of carbon, but the results were inconclusive. The experiments were continued by actual trials in guns with steels containing 0.31 to 0.35 per cent. of carbon and 0.8 per cent. of manganese. The conclusion arrived at appears to have been that resistance to erosion varies with the amount of work put on the steel, and that by forging the resistance of steel to erosion was raised. The trial was continued on similar lines with steels containing 0.24 to 0.31 per cent. of carbon and 0.55 to 0.58 per cent. of manganese. The best steel

* Vieille,⁽³⁵⁾ Siwy,⁽²⁹⁾ Bethlehem Steelworks, Indian Head Naval Proving Ground, see Yarnell,⁽³⁹⁾ Earle,⁽¹³⁾ and Zimmermann.⁽⁴⁰⁾

of this series had the lowest carbon, the lowest manganese, and also showed very marked fibrous structure. Noble, however, found in further vent trials that the amount of work put on the steel of the vents made no difference to the amount of erosion. In later trials of steels containing 0.45 to 0.55 per cent. of carbon the Superintendent of the Royal Gun Factory concluded that oil-hardening had no beneficial effect, having found an untreated barrel to be slightly but unmistakably better than one of the same steel oil-hardened.

Later experiments carried out in experimental erosion barrels with cordite M.D. 4 $\frac{1}{4}$ placed steels in the following order of merit :

Order.	Chemical Composition.				
	Carbon. %	Manganese. %	Nickel. %	Chromium. %	Molybdenum. %
1	0.35	0.62	...	...	...
2	0.52	0.82	...	...	...
2 eq.	0.37	0.82	3.15	...	...
3	0.32	0.27	...	1.37	1.60
4	0.31	0.65	5.96	...	...
5	0.31	0.46	3.7	1.85	...

In 1905 A. Mallock ⁽²¹⁾ reported results of erosion vent experiments in which he employed a conical vent (Fig. 36) fitted to

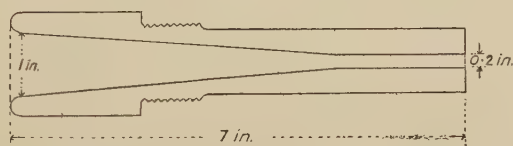


FIG. 36.—Erosion Vent used by Mallock.

a closed vessel. He found that erosion was very small, in the circumstances of his test, up to a charge of 4 oz. of cordite (pressure, 3 tons per sq. in.), and then increased in direct ratio with an increase of charge and pressure (Fig. 37). Sir Andrew Noble, ⁽²²⁾ in his erosion vent experiments with different propellants, also found a linear relation between erosion and weight of charge

(and consequent pressure). With Mark I. cordite the straight line expressing the relation between erosion and density of loading passed through the origin, but with tubular nitro-cellulose erosion was practically nil up to a density of loading of 0.06 (pressure, 3 tons per sq. in.), while with cordite and 40 per cent. water it

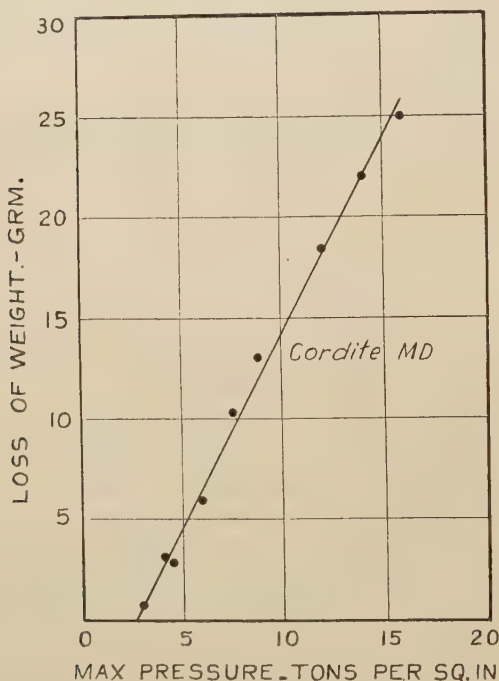


FIG. 37.—Relation between the Amount of Erosion and the Maximum Pressure (Mallock).

was nil up to a density of loading of 0.13. Beyond these points erosion was nearly proportional to increase in weight of charge or increase in pressure (Fig. 38).*

An important series of experiments made by Sir Andrew Noble, illustrating the influence of the calorific power of propellants, was that in which equal charges of cordites of different

* A. Noble, *Philosophical Transactions*, 1905, [A], vol. ccv. pp. 201-236 (Plate XIII.).

compositions were fired through erosion vents. Passing from cordite with 10 per cent. of nitro-glycerine to that with 60 per

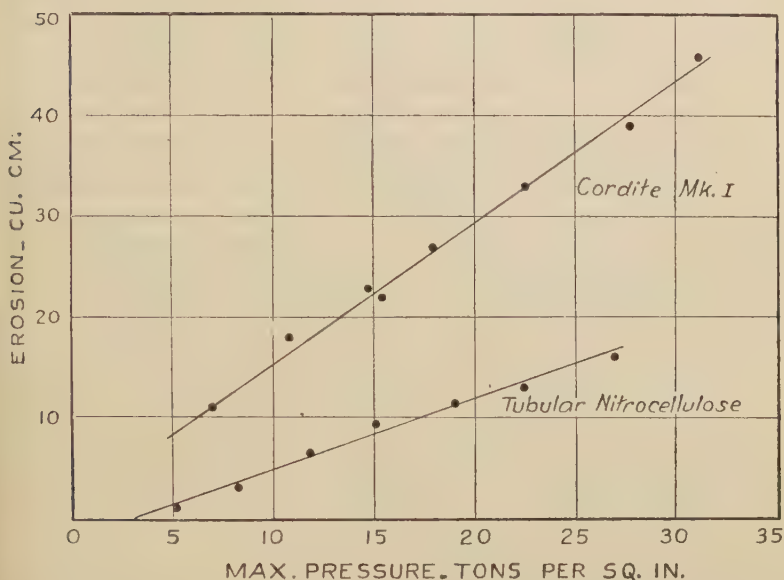


FIG. 38.—Relation between the Amount of Erosion and the Maximum Pressure (Noble).

cent., he found that the heat generated had increased by 60 per cent., but the erosion was greater by nearly 500 per cent.

In 1909, erosion vent tests were made on three heat-treated steels of the following compositions :

	Carbon Steel.	Nickel Steel.	Tungsten Steel.
Carbon, per cent. . .	0.29	0.39	0.61
Manganese, „ . .	0.83	0.63	0.27
Nickel, „ . .	...	3.68	...
Tungsten, „ . .	...	...	4.76

The tungsten steel was inferior to nickel or carbon gun steel in resisting erosion. The carbon steel was better than the nickel steel, thus confirming previous results.

The Ordnance Board in 1910 summarised the existing evidence, and concluded that "the nature of the powder does not, so far as is known, affect the relative resistance of the various alloys of iron to erosion; up to the present, experience has shown that, *cæteris paribus*, the purer the metal the less it erodes, therefore large percentages of carbon and addition of nickel, chromium, &c., lessen resistance to erosion."

It is of interest to note that Brearley discovered stainless steel in the course of an extensive research on the resistance to erosion of various steels in reference to their use for rifles and naval guns.* There is, however, no record of any trials having been made with this steel in guns, though its experimental use in machine-gun barrels is referred to later.

The Present Series of Erosion Vent Experiments.

The experiments described in this Report differ from earlier series in that they were carried out on a wider selection of materials, including steels and propellants only recently produced. The effect of several variations in the conditions of experiment has also been investigated.

The apparatus used in these vent plug experiments is shown diagrammatically in Fig. 39, *A*. Three firing vessels were used, the internal capacities being 27, 66, and 180 cu. in. respectively. They differed from the ordinary type of "closed vessel" only in having an additional breech-fitting in which the vent plug was inserted.

Propellant charges were placed in the vessel and fired by connecting a battery to the terminals *T*, thereby rendering the wire *S* incandescent. The chamber pressure developed was measured by means of a radial gauge with copper or lead crushers. The hot gases generated by the burning of the propellant could only escape by passing through the axial hole of the vent plug, which was weighed before and after firing in order to determine the loss of weight caused by erosion. Except where otherwise stated, a fresh vent was used for each round, and the loss of weight measured was that produced by firing one charge of the propellant.

The design of the vent plug used is shown in Fig. 39, *B*.

* J. H. G. Monypenny, "Stainless Iron and Steel," 1926, p. 7.

The diameter of the axial hole was usually 2 mm., but larger diameters were employed in some cases.

The chemical composition and mechanical properties of the metals and alloys used for vent plugs are given in Table I. (p. 130).

The general character of the curves showing the amount of

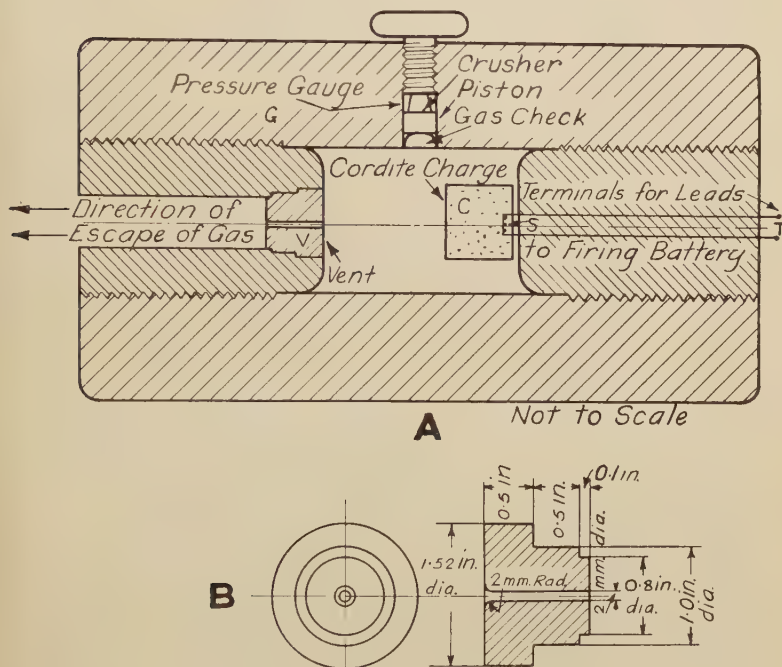


FIG. 39.—Erosion Experiments.
A, Diagram of firing vessel. B, Design of vent.

erosion against pressure is illustrated by Fig. 40, in which the data for oil-hardened and tempered nickel-chromium steel are given. Under the conditions of this experiment, there was a critical chamber pressure of about 2 tons per sq. in. below which the weight of metal removed was extremely small, and beyond which the erosion increased rapidly and almost proportionally to the increase in pressure. The characteristic erosion-pressure diagram for all the metals and alloys examined is of this type, which is in agreement with the observations of Sir Andrew Noble

TABLE I.—*Chemical Analysis and Mechanical Properties of Materials used, together with their Relative Erodibility as Measured in Erosion Vent Experiments.*

Mark.	Material.	Chemical Composition.						Condition.	Brinell Hardness No.	Yield Point. Tons per sq. in.	Max. Load. Tons per sq. in.	Relative Erodibility to nearest 0.5 (see Tables II. and III.).
		Carbon, %	Silicon, %	Manganese, %	Sulphur, %	Phosphorus, %	Nickel, %	Chromium, %				
<i>ECP</i>	Armco iron	0.03	0.01	0.02	0.002	0.013	...	...	109	12	21	< 4.0
<i>CMS</i>	Mild steel	0.16	0.05	0.51	0.076	0.070	...	...	111	13	26	> 4.0
<i>AYM</i>	Carbon gun steel	0.42	0.13	0.80	0.036	0.037	...	...	179	24	40	4.5†
<i>CDN</i>	Carbon steel with high manganese	0.39	0.11	1.12	0.035	0.025	...	...	183	25	39	4.5
<i>DDO</i>	Tungsten steel	0.36	0.09	2.24	0.027	0.027	...	...	239	40	50	4.5
<i>DRD</i>	Nickel gun steel	0.30	0.09	0.17	0.045	0.027	...	...	179	27	37	4.5
<i>CFW</i>	Nickel-chromium gun steel	0.32	0.13	0.66	0.026	0.023	3.63	0.05	198	30	43	4.5
<i>CFX</i>	Nickel-chromium steel	0.29	0.12	0.56	0.023	0.030	3.67	0.62	234	37	49	4.5
<i>GVR</i>	Nickel-chromium-molybdenum steel	0.25	0.26	0.45	0.015	0.010	3.39	0.75	230	38	48	4.5
<i>CNO</i>	Nickel-chromium-vanadium steel	0.28	0.15	0.48	0.032	0.028	2.45	0.65	259	47	56	4.5
<i>GME</i>	Chromium-vanadium steel	0.36	0.23	0.37	0.037	0.024	3.36	0.90	245	43	51	4.5
<i>DOO</i>	Stainless steel	0.28	0.12	0.21	0.037	0.022	...	1.2	306	54	64	4.5
<i>AYR</i>	Low-carbon stainless steel	0.13	0.15	0.21	0.080	0.024	0.20	12.37	255	42	54	9.0
<i>FYL</i>	High-chromium stainless steel	0.23	0.11	0.15	0.045	0.040	0.20	12.40	202	30	41	9.0
<i>FYO</i>	Austenitic stainless steel	0.15	0.16	0.11	< 0.005	0.018	2.04	17.9	296	47	62	10.0
<i>FAE</i>	Austenitic stainless steel	0.37	0.11	1.30	0.02	0.03	35.6	11.0	171	13	54	11.0
<i>FOH</i>	Austenitic nickel steel	< 0.02	0.13	0.30	< 0.01	0.01	34.7	11.0	216	17	42	10.5
<i>FNO</i>		0.11	0.11	0.37	0.025	0.013	36.7	0.005	175	35	39	7.0
<i>FNP</i>									217	36	46	7.0
<i>EHT</i>	Nickel, pure								172	...	...	6.5
<i>CXL</i>	Monel metal (nickel, 70%; copper, 28%; remainder, chiefly iron and manganese)								172	...	...	13.0
<i>CYE</i>	Copper, pure, electrolytically refined								60	...	...	15.0
<i>CYD</i>	Brass (copper, 70%; zinc, 30%)								118	...	...	23.0

Non-Ferrous Metals and Alloys.

* Also tested in the annealed condition (Table IX.).

† The value for all steels returned as 4.5 fell between 4.3 and 4.8.

and of Mallock. The diagram is made up of two approximately straight lines, meeting at a point of inflexion which for all steels is at about 2 tons per sq. in. Below this pressure the curves for steels (including alloy steels of high nickel and chromium content) are almost identical, showing practically no loss of weight. Above this pressure they show marked differences in slope, due

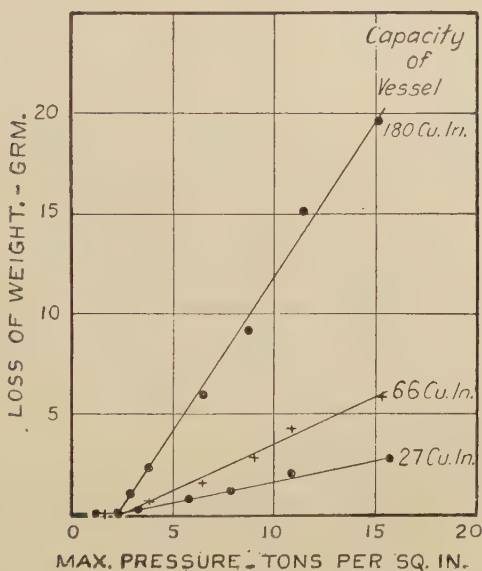


FIG. 40.—Erosion of Nickel-Chromium Steel (CFX) Vents by cordite M.D. $2\frac{1}{4}$ (lot B) in vessels of 27, 66, and 180 cu. in. capacity.

to differences in composition or to varying conditions of the experiment.

The characteristic form of the erosion-pressure curve makes it easy to give a numerical indication of the behaviour of any particular material by a statement of the slope of the curve beyond the point of inflexion.

If W is the loss of weight by erosion with a chamber pressure P , and p the pressure at the point of inflexion of the curve (the loss of weight at this point, w , being negligible in comparison with W), then the slope of the curve is expressed by $\frac{W}{P-p}$. To

obtain a convenient numerical value, W is expressed in decigrammes, the pressures being in tons per sq. in.

This value (the "erodibility" E) may be used as a figure of merit for the material under consideration when the size of vessel, size of vent, and nature of the propellant are unchanged; the lower the figure the less the erodibility. Thus for the nickel-chromium steel referred to in Fig. 40, p is 2 tons per sq. in. and E (for the 66 cu. in. vessel) is 4.5. Figures for relative erodibility determined under the same standard condition are inserted in Table I.

Reproducibility of Results.—After some preliminary work had been completed with a sample of cordite referred to as lot A , a sufficient supply of cordite M.D. 2 $\frac{1}{4}$, referred to as lot B , was secured and used for all subsequent experiments.

The maximum pressure produced in the closed vessel by the same charge of propellant showed considerable variations, the extreme values differing by 10 per cent. for the higher pressures, and by an even greater percentage for low pressures. This may have been due partly to variability of coppers, and partly to the fact that the charge occupied only a small part of the total volume, and that wave pressure to some extent affected the maximum recorded. It is therefore clear that too much weight should not be given to an individual result, though the general character of the curve as a whole represents the behaviour of the steel with a degree of accuracy which justifies the expression of the figure for erodibility to the nearest 0.5, as shown in the last column of Table I. In some instances discrimination between materials of almost equal erodibility tested under identical conditions is sufficient to justify the recognition of slightly smaller differences. Whenever a new series of experiments was started at least one steel on which results had been previously obtained was included to preserve a standard of comparison. This precaution was necessary, as, even when charges obtained from the same lot of cordite were employed, there was an occasional variation in the results given by the standard steels.

The extreme variations so obtained are shown by the following figures (see first table on p. 133).

The relative erodibility of different steels deduced from any one series of tests carried out at the same time was, however,

Nickel-Chromium Steel.

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm.
Propellant, cordite M.D. 2½.

Charge. Grains.	Cordite Lot A.		Cordite Lot B.		Cordite Lot B.	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
3100	14.5	6.7	15.3	5.7	14.6	6.9
2500	11.1	5.1	10.9	4.4	11.4	4.7
2000	8.3	3.9	8.9	2.9	8.8	3.3
1500	6.0	2.6	6.4	1.5	6.5	1.8
1000	3.7	1.5	3.9	0.6	4.0	0.6
500	1.7	0.013	1.3	0.047	1.7	0.08
	$E = 5.6$		$E = 4.5$		$E = 5.3$	

consistent, as shown by the following results obtained in three typical series of tests in which more than one of the standard steels was included :

Mark.	Steel.	Cordite M.D. 2½.		
		Lot A.	Lot B.	
			E	E
CMS	Mild steel	4.9	4.0	...
AYM	Carbon steel	5.4	4.7	...
CFW	Nickel steel	5.6	4.7	5.2
CFX	Nickel-chromium steel	5.6	4.5	5.2

The results of any one series are therefore strictly comparable among themselves, but in assigning relative figures to material of approximately equal erodibility due allowance must be made for slight but unexplained differences shown by the standard steel in the different circumstances of the test.

Detailed results are given in Tables II. and III.

Table II. shows results obtained with cordite lot A with which the standard steels always gave about 5.5; in Table III. are collected all series in which the standard steels gave about 4.7. Typical diagrams are shown in Figs. 41 to 43.

TABLE II.—*Erosion Tests of Vent Plugs fitted to Firing Vessel.*(First series, in which the standard nickel steel gave $E = 5.6$.)

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm.

Propellant, cordite M.D. 2½ (lot A).

Charge. Grains.	Mild Steel (CMS).		Carbon Gun Steel (AYM).		Nickel Gun Steel (CFW).		Nickel-Chromium Gun Steel (CFX).		Stainless Steel (AYE).		Monel Metal (CXL).	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
3100	16.1	6.69	14.7	6.84	14.5	6.95	14.5	6.72	14.5	10.72	...	...
2500	11.6	4.63	11.5	4.73	11.5	5.18	11.1	5.07	11.5	8.57	10.9	10.56
2000	8.3	3.56	8.3	3.79	8.3	3.92	8.3	3.87	8.2	7.49	8.8	7.94
1500	6.4	2.48	6.1	2.76	6.0	2.81	6.1	2.55	6.2	4.57	6.2	5.64
1000	3.8	1.18	3.7	1.52	3.8	1.59	3.7	1.50	3.8	2.40	3.9	2.54
500	1.7	0.02	1.7	0.03	1.5	0.01	1.7	0.01	1.6	0.05	1.8	0.034
200	1.7	0.04	...	...	...	...	1.7	0.02	...	...	...	...
3 charges of 500	...	...	0.54	0.001	0.54	0.01	0.56	0.002	0.55	0.001	0.58	0.002
	$E = 4.9$		$E = 5.4$		$E = 5.6$		$E = 5.6$		$E = 9.0$		$E = 13.0$	

TABLE III.—*Erosion Tests of Vent Plugs fitted to Firing Vessel.*(Second and subsequent series in which the standard nickel steel gave $E = 4.7$.)

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm. Propellant, cordite M.D. 2½ (lot B).

Charge. Grains.	1.1 per cent. Manganese- Carbon Steel (CDN).			2.2 per cent. Manganese- Carbon Steel (CDO).			1.7 per cent. Tungsten- Carbon Steel (DRD).			Carbon Gun Steel (CFM).			Nickel- Chromium Gun Steel (CFX).			Nickel- Chromium- Molybdenum Steel (CNO).			Nickel- Chromium- Vanadium Steel (GME).			Chromium- Vanadium Steel (DOO).		
	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.
3100	15.5	5.14	15.4	6.59	15.5	5.97	15.5	6.22	14.7	5.95	14.2	5.60	15.3	5.72	15.0	5.50	15.1	5.92	14.4	5.23	15.1	5.92	14.4	5.23
2500	11.4	4.01	11.3	4.24	11.3	4.29	11.4	4.61	11.5	4.14	11.5	4.23	10.3	4.38	10.9	4.39	11.6	4.97	11.3	4.23	11.6	4.97	11.3	4.23
2000	9.0	2.41	8.9	2.82	8.9	3.33	9.0	2.61	9.0	3.62	9.0	3.37	8.9	2.92	8.8	3.03	9.0	3.40	8.8	2.98	9.0	3.40	8.8	2.98
1500	6.8	1.45	6.8	1.83	6.8	1.80	6.9	2.16	6.8	2.06	6.7	2.10	6.5	1.49	6.7	1.96	6.8	2.21	6.2	1.60	6.8	2.21	6.2	1.60
1000	4.1	0.86	4.2	1.07	4.1	0.94	4.2	0.88	4.0	0.46	4.1	0.56	3.9	0.58	4.0	0.62	4.0	1.16	3.8	1.03	4.0	1.16	3.8	1.03
500	1.9	0.02	1.8	0.06	1.9	0.09	1.9	0.06	1.7	0.022	1.8	0.03	1.5	0.05	1.7	0.02	1.6	0.01	1.7	0.01	1.6	0.01	1.7	0.01
3 charges of 500	2.0	0.08	1.9	0.12	1.9	0.08	1.9	0.10	...	...	1.7	0.05	1.3	0.02	1.7	0.02	1.6	0.03	1.7	0.01	1.6	0.03	1.7	0.01
	$E = 3.8$			$E = 4.6$			$E = 4.6$			$E = 4.7$			$E = 4.5$			$E = 4.4$			$E = 4.7$			$E = 4.3$		

Charge. Grains.	Low-Carbon Stainless Steel (FXL).			Stainless Steel (AYE).			High-Chromium Stainless Steel (FTQ).			Austenitic Stainless Steel (FKE). Cr 20%; Ni 8%.			Austenitic Stainless Steel (FOH). Cr 11%; Ni 36%.			Austenitic Nickel Steel (FNO). Ni 35%.			Austenitic Nickel Steel (FNP). Ni 37%.			Nickel (BHT).			Copper (CFE).			70/30 Brass (CYD).		
	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.	Pressure. Tons per sq. in.	Loss of Weight. Gm.
3100	15.3	10.48	14.5	10.02	15.0	11.55	14.7	12.88	15.4	12.16	15.4	9.37	15.4	9.34	15.4	8.16	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2500	11.8	9.07	11.5	8.69	11.7	10.61	11.7	10.85	11.7	10.35	11.1	6.82	11.3	6.90	11.4	5.92	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2000	9.3	7.96	9.0	7.51	9.3	7.90	9.3	9.84	...	...	8.9	4.94	8.9	4.76	9.0	4.31	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1500	7.1	6.04	7.0	5.41	7.1	6.39	7.1	6.55	7.1	6.21	6.3	2.82	6.3	2.98	7.0	2.57	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1000	4.2	3.62	4.0	1.76	4.3	1.92	4.2	1.99	4.3	3.01	3.8	2.04	3.9	1.68	4.1	0.63	...	...	...	...	...	...	...	...	...	...	...	...	...	...
500	2.0	0.14	1.7	0.02	2.0	0.19	2.0	0.08	2.0	0.33	1.3	0.03	1.5	0.14	1.9	0.004	...	...	...	...	...	...	...	...	...	...	...	...	...	...
3 charges of 500	2.0	0.37	...	...	2.0	0.25	2.0	0.32	2.0	0.65	1.6	0.12	1.6	0.36	2.0	0.02	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	$E = 9.2$			$E = 9.0$			$E = 10.0$			$E = 11.0$			$E = 10.2$			$E = 7.1$			$E = 7.2$			$E = 6.6$			$E = 15.0$			$E = 23.0$		

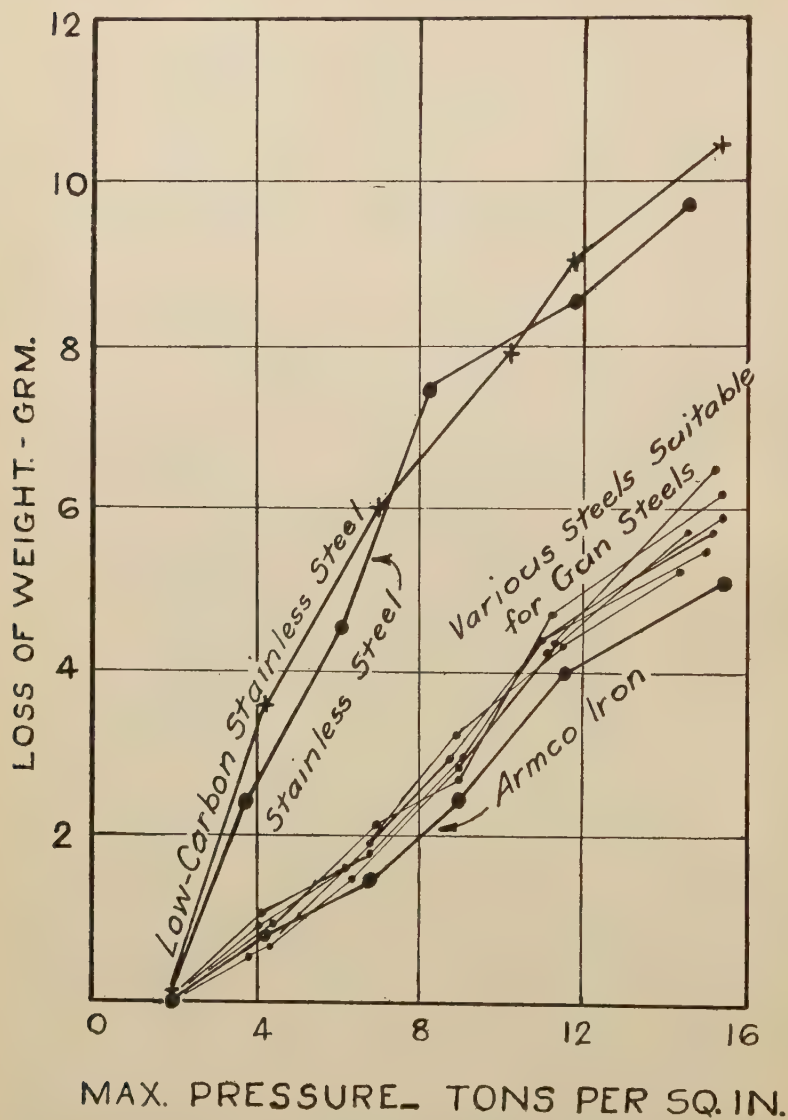


FIG. 41.—Erosion of Stainless Steels compared with that of Actual and Other Possible Gun Steels and of Armco Iron. (Cordite M.D. $2\frac{1}{4}$; capacity of vessel, 66 cu. in.; diam. of vent, 2 mm.)

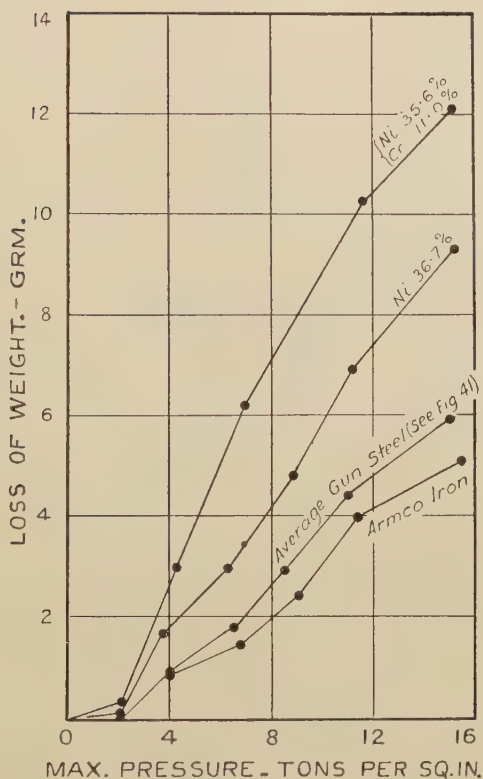


FIG. 42.—Erosion of Austenitic Steels compared with that of Gun Steels and of Armco Iron. (Cordite M.D. 2 $\frac{1}{4}$; capacity of vessel, 66 cu. in.; diam. of vent, 2 mm.)

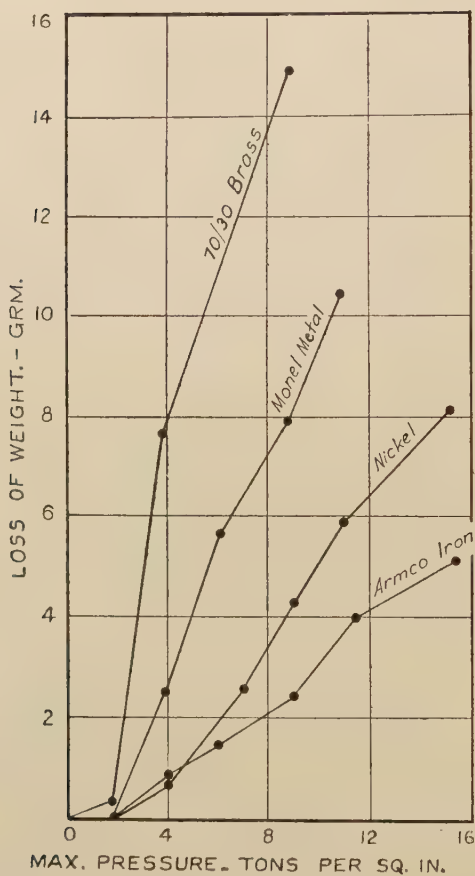


FIG. 43.—Erosion of Non-Ferrous Metals compared with that of Armco Iron. (Cordite M.D. $2\frac{1}{4}$; capacity of vessel, 66 cu. in.; diam. of vent, 2 mm.)

Effect of Size of Vessel.—Experiments were carried out on three steels in the three different vessels of 27, 66, and 180 cu. in. capacity respectively. The results obtained in the 66 cu. in. vessel have already been given in Tables II. and III.; those

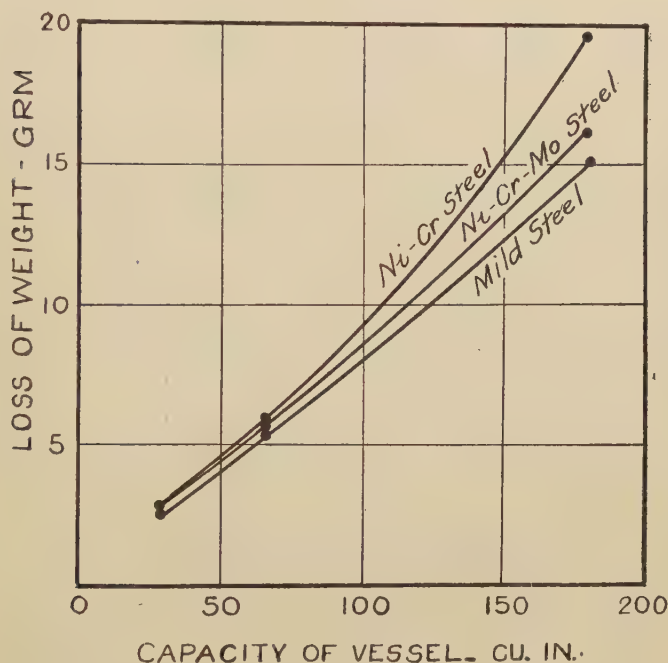


FIG. 44.—Effect of Size of Firing Vessel on Amount of Erosion of Vent Plugs. (Cordite M.D. $2\frac{1}{4}$; pressure, 15 tons per sq. in.)

obtained in the other closed vessels are given in Tables IV. and V., together with a summary in Table VI. The relative erodibility of the steels remained about the same under these conditions (Fig. 44). No regular differences could be detected in the amount of erosion at a given pressure per 1000 grains of propellant charge fired in the small, medium, and large vessels. The loss of weight of similar vents of the same steel per 1000 grains of propellant was dependent only on the pressure (Table VII.).

TABLE IV.—*Erosion Tests in Small Firing Vessel.*

Capacity, 27 cu. in. Diameter of vent, 2 mm.
 Propellant, cordite M.D. 2½ (lot B).

Charge. Grains.	No. of Charges Fired.	Mild Steel (CMS).		Nickel-Chromium Steel (CFA).		Nickel-Chromium- Molybdenum Steel (CNO).	
		Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
1350	1	15.5	2.50	15.6	2.74	15.1	2.66
1100	1	10.8	1.76	10.8	2.12	11.2	2.12
800	1	7.9	1.13	7.9	1.06	8.1	1.16
600	1	5.8	0.54	5.8	0.82	6.0	0.96
600	3	5.7	1.42	5.6	1.95	5.8	1.93
470	1	...	...	...	...	4.2	0.19
470	3	4.4	0.49	4.3	0.98	4.1	1.09
350	1	3.5	0.09	3.3	0.22	3.1	0.02
350	3	3.2	0.13	3.1	0.33	3.1	0.42
250	1	...	...	...	...	2.0	0.024
250	3	2.0	0.025	2.2	0.020	2.0	0.032
150	1	1.3	0.004	1.3	0.003	1.2	0.006
150	3	...	...	...	...	1.1	0.011
		$E = 1.7$		$E = 2.1$		$E = 2.1$	

TABLE V.—*Erosion Tests in Large Firing Vessel.*

Capacity, 180 cu. in. Diameter of vent, 2 mm.
 Propellant, cordite M.D. 2½ (lot B).

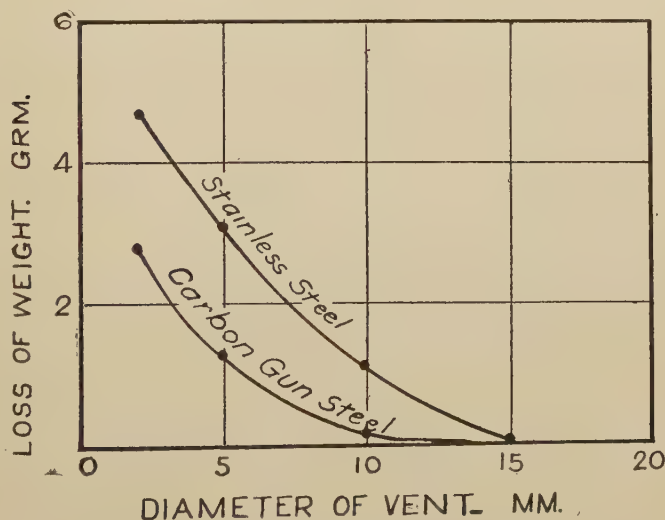
Charge. Grains.	No. of Charges Fired.	Mild Steel (CMS).		Nickel-Chromium Steel (CFA).		Nickel-Chromium- Molybdenum Steel (CNO).	
		Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
9840	1	15.1	15.13	15.1	19.69	15.3	16.10
7980	1	11.3	13.71	11.3	15.10	11.8	11.92
6150	1	8.7	9.11	8.7	9.18	9.0	9.31
4590	1	6.4	5.57	6.5	6.01	6.5	5.74
2920	1	3.7	2.28	3.7	2.32	3.7	2.43
2350	1	3.1	1.48	3.0	1.03	3.0	0.68
2350	3	3.0	3.66	3.2	4.38	3.0	4.80
1530	1	1.9	0.13	1.9	0.02	1.9	0.33
1530	3	2.2	0.41	2.2	0.30	2.3	1.76
984	1	1.2	0.02	1.2	0.009	1.2	0.02
984	3	1.3	0.08	1.3	0.058	1.3	0.06
		$E = 12.4$		$E = 15.2$		$E = 12.9$	

TABLE VI.—*Relative Erodibility of Vents fitted to Firing Vessels of Different Sizes.*

Capacity of Vessel.	Small, 27 cu. in.	Medium, 66 cu. in.	Large, 180 cu. in.
Relative erodibility, <i>E</i> :			
Nickel-chromium steel (<i>CFX</i>)	2.1	4.5	15.0
Nickel - chromium - molybdenum steel (<i>CNO</i>)	2.1	4.5	13.0
Mild steel (<i>CMS</i>)	1.7	4.0	12.5
Relative capacity of vessels	2.0	4.9	13.3

TABLE VII.—*Loss of Weight of Vents fitted to Firing Vessels of Different Sizes expressed in Grm. per 1000 Grains of Propellant Charge (Cordite M.D. 2½).*

Approximate Pressure. Tons per sq. in.	15.	11.	8.	6.	4.
Nickel-chromium steel (<i>CFX</i>) { Small vessel Medium „ Large „	2.0	1.9	1.3	1.4	0.6
	1.8	1.7	1.5	1.0	0.6
	2.0	1.9	1.5	1.3	0.7
Nickel-chromium-molybdenum steel (<i>CNO</i>) { Small vessel Medium „ Large „	2.0	1.9	1.4	1.6	0.4
	1.8	1.8	1.5	1.3	0.6
	1.6	1.5	1.5	1.2	0.8

FIG. 45.—Effect of Size of Axial Hole of Vent on Erosion.
(Charge, 1500 grains of cordite M.D. 2½.)

Effect of Size of Vent.—The effect of the size of the axial hole on the amount of erosion is shown by the data given in Table VIII. With the same weight of propellant, the loss of weight due to erosion falls off rapidly with an increase of diameter of the axial hole, because a smaller proportion of the total volume of gas generated comes into contact with the surface of the vent, and also because the maximum pressure produced by a given charge diminishes with the increased size of the orifice. Steels, however, preserve the same order of relative erodibility (Fig. 45, p. 141).

TABLE VIII.—*Effect of Size of Axial Hole of Vent on Erosion.*

Charge, 1500 grains of cordite M.D. 2½.

Diameter of Axial Hole of Vent.	2 mm.	5 mm.	10 mm.	15 mm.
Average pressure. Tons per sq. in. . . .	6.3	5.9	5.0	3.8
Loss of weight of vent plugs. Grm.				
Carbon gun steel (<i>AYM</i>)	2.8	1.3	0.15	0.006
Nickel gun steel (<i>CFW</i>)	2.0	1.2	0.14	0.004
Stainless steel (<i>AYR</i>)	4.7	3.1	1.15	0.005

Effect of Heat Treatment.—Comparative experiments with vent plugs of annealed and of oil-hardened and tempered steel indicate that heat treatment has little effect on the erosion of the metal (Table IX.). The same applies to the rolled and the annealed conditions of non-ferrous alloys.

Effect of Lubrication of the Steel Surface.—As indicated in a previous section, examination of worn-out tubes, lubricated or not lubricated throughout their life, showed that the surface cracking was almost identical at similar positions throughout the tube, and that lubrication was without effect on the character of the hardened skin. The effect of a film of graphite grease on the loss of weight of erosion vents has been determined with nickel gun steel (*CFW*) and cordite M.D. 2½ (lot *B*). Ten charges of 1500 grains were fired through dry vents (diameter, 10 mm.), and also through similar vents covered before each round with a layer of graphite grease. The average maximum pressure in each case was 4.7 tons per sq. in. and the loss of weight as follows :

Dry vents, 2.14 grm.; lubricated vents, 1.60 grm. The lower loss of weight for the lubricated vents was probably due to the heat absorbed in removing the film forming an appreciable proportion of the total heat communicated by the gas to the short

TABLE IX.—*Effect of Heat Treatment on Erosion.*

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm.
Propellant, cordite M.D. 2½ (lot A).

	Charge, 1500 Grains.		Charge, 3100 Grains.	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
Stainless steel { O.-H. and T. .	6.2	4.6	14.5	10.7
	Annealed . .	6.1	14.4	11.1
Nickel gun steel { O.-H. and T. .	6.0	2.8	14.5	7.0
	Annealed . .	6.1	14.2	7.1
Nickel-chromium { O.-H. and T. .	6.1	2.6	14.6	6.7
	gun steel { Annealed . .	6.1	14.2	6.8
Carbon gun steel { O.-H. and T. .	6.1	2.8	14.7	6.8
	Annealed . .	6.2	14.2	7.2
	Charge, 1000 Grains.		Charge, 2500 Grains.	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
Monel metal { Rolled . . .	3.9	2.5	10.9	10.6
	Annealed . . .	4.0	11.1	10.7

O.-H. = oil-hardened; T. = tempered.

channel of the vent. In a gun the total heat available would be enormously greater. The lubricant, if used, is generally applied in front of the driving band. The thickness of the film after the passage of the driving band would therefore be slight, and its protective effect against the action of the hot gases probably negligible.

Effect of the Calorific Power of the Propellant.—The influence of the calorific power of the propellant on the amount of erosion produced has been the subject of many investigations.*

* Noble,⁽²²⁾ Vieille,⁽³⁵⁾ Jones,^(16, 17) Yarnell.⁽³⁹⁾

Tests have been made on erosion vents of several steels with different propellants, or with other experimental materials more

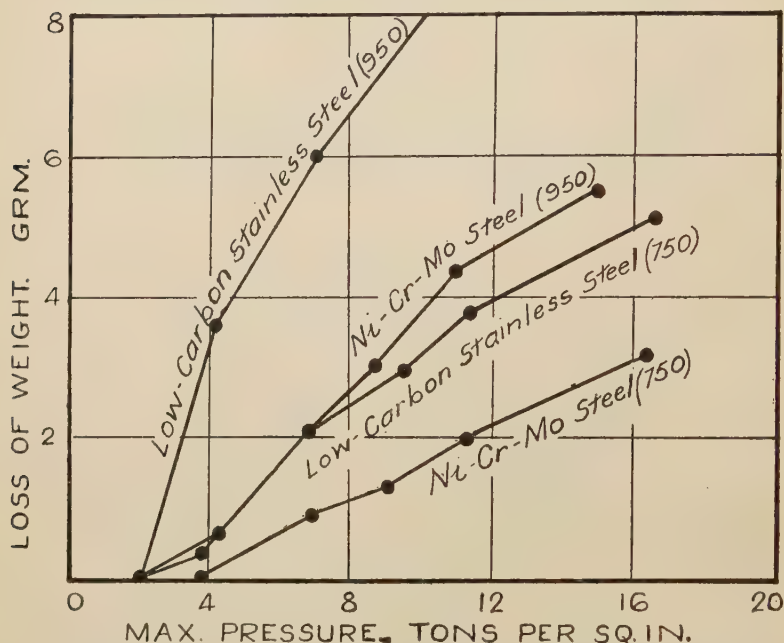


Fig. 46.—Erosion of Stainless Steel (*FXL*) and of Nickel-Chromium-Molybdenum Steel (*CNO*) by Propellants of 950 cal. and 750 cal. calorific value. (Capacity of vessel, 66 cu. in.; diam. of vent, 2 mm.)

or less suitable for use as propellants. These included the following :

Cordite M.D. .	Nitro-glycerine 30, gun-cotton 65, mineral jelly 5 per cent.,
Cordite R.D.B.	Nitro-glycerine 42, nitro-cellulose 52, mineral jelly 6 per cent.,
N.C.T. .	Nitro-cellulose with 0.5 per cent. diphenylamine,

and other modified or experimental propellants here referred to as *A*, *B*, *C*, &c.

Detailed results of tests, including the calorific power of each propellant, are given in Tables X. to XII., and the behaviour of the various steels is illustrated in Figs. 46 and 47. With

the exception of cordite M.D. 45, the propellants were all of a size to give approximately the same rate of burning as cordite M.D. 2 $\frac{1}{4}$.

For any given steel the loss of weight due to erosion is highest with the slow-burning cordite M.D. 45. This is true for the same

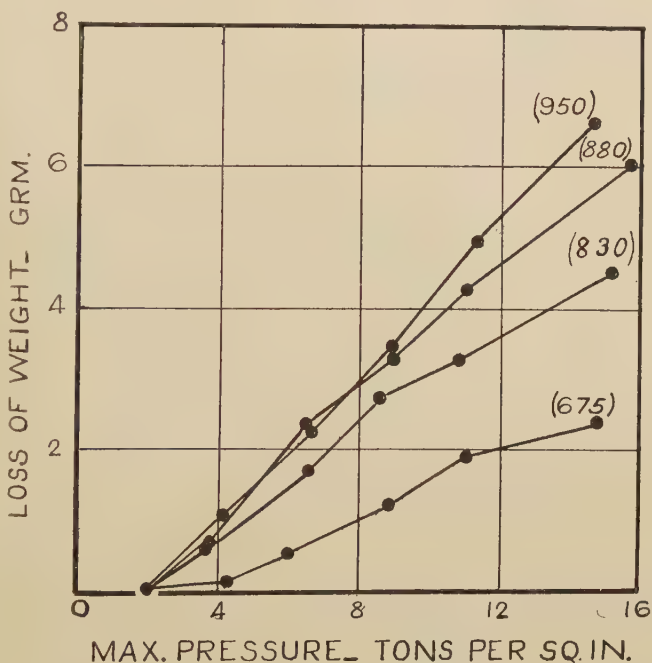


FIG. 47.—Erosion of Nickel-Chromium Steel (*GVR*) by Various Propellants, the calorific values of which are indicated in brackets. (Capacity of vessel, 66 cu. in.; diam. of vent, 2 mm.)

maximum pressure and also for the same weight of charge, except at low pressures, when the erosion produced is small in amount. The passage of the hot gases through the vent occupies a longer time when the thicker cordite is used, and the transfer of heat to the vent is therefore greater. With propellants of the same size, the loss of weight due to erosion falls off very regularly with the decrease in calorific value of the propellant and the consequent decrease of the maximum temperature attained by the hot gases.

TABLE X.—*Effect of the Propellant on Erosion of Vents fitted to a Firing Vessel.*

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm.
 Weight of charge in each instance : (1) 2500 grains ; (2) 1500 grains.

Results of tests with cordite M.D. 2½ are given in full in Table II.
 (Standard nickel steel gave $E = 5.4$.)

Material of Vent.	Cordite M.D. 45 (950 cal.).		Cordite M.D. 2½ (lot A) (950 cal.).		Cordite R.D.B. 2½ (930 cal.).		N.C.T. 5 (810 cal.).	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
Mild steel (<i>CMS</i>)	9.4	4.92	11.6	4.63	11.4	3.95	9.9	2.22
	5.0	2.20	6.4	2.48	6.1	1.23	5.2	0.54
	$E = 6.0$		$E = 4.8$		$E = 4.3$		$E = 2.8$	
Carbon gun steel (<i>AYM</i>)	9.7	5.00	11.5	4.73	12.1	3.85	9.9	2.28
	4.7	3.17	6.1	2.76	5.9	1.75	5.8	1.03
	$E = 5.8$		$E = 4.9$		$E = 3.8$		$E = 2.9$	
Nickel gun steel (<i>CFW</i>)	9.3	5.51	11.6	5.18	11.6	4.08	10.0	2.74
	4.8	2.60	6.0	2.81	6.0	1.97	5.8	0.51
	$E = 6.5$		$E = 5.4$		$E = 4.2$		$E = 3.5$	
Nickel-chromium gun steel (<i>CFX</i>)	9.3	5.56	11.1	5.07	11.6	3.98	9.9	2.55
	5.0	2.28	6.0	2.55	6.2	1.29	5.0	0.84
	$E = 7.0$		$E = 5.5$		$E = 4.2$		$E = 3.2$	
Stainless steel (<i>AYR</i>)	9.0	9.48	11.5	8.57	12.1	6.21	10.0	5.35
	4.8	6.09	6.2	4.57	6.1	3.60	5.8	1.73
	$E = 11.5$		$E = 9.0$		$E = 6.2$		$E = 5.5$	

TABLE XI.—*Effect of the Propellant on Erosion of Vents fitted to a Firing Vessel.*

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm.

Results of tests with cordite M.D. 2½ are given in Table III.
(Standard nickel steel gave $E = 4.7$.)

Charge B (880 cal.).			Charge N.C.T. (810 cal.).			Charge E (750 cal.).		
Charge. Grains.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Charge. Grains.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Charge. Grains.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
(a) Vents of Nickel-Chromium Steel (CFX).								
3380	15.8	5.37	3620	16.0	3.87	3670	16.5	2.90
2440	10.9	3.83	2620	10.9	2.63	2650	11.3	1.70
2010	8.8	2.73	2175	8.7	1.70	2200	9.2	1.12
1500	6.6	1.58	1625	6.7	0.64	1650	6.9	0.77
920	3.7	0.78	985	3.6	0.28	1000	3.8	0.07
400	1.4	0.003	420	1.3	0.005	430	...	...
3 at 400	1.5	0.006	3 at 420	1.3	0.008	3 at 430	1.4	0.005
$E = 3.9$			$E = 2.8$			$E = 1.9$		
(b) Vents of Nickel-Chromium-Molybdenum Steel (CNO).								
3380	16.1	6.31	3620	15.9	4.77	3670	16.4	3.20
2440	10.9	3.80	2620	10.9	2.74	2650	11.3	1.98
2010	8.8	2.40	2175	8.7	2.21	2200	9.2	1.33
1500	6.6	1.92	1625	6.7	0.56	1650	6.9	0.91
920	3.7	0.38	985	3.6	0.08	1000	3.8	0.02
400	1.4	0.004	420	1.3	0.003	430	1.4	0.002
3 at 400	1.5	0.007	3 at 420	1.3	0.006	3 at 430	1.4	0.008
$E = 4.2$			$E = 3.3$			$E = 2.1$		

Charge A (912 cal.).			Charge E (750 cal.).				
Charge. Grains.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Charge. Grains.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
(c) Vent of Nickel Gun Steel (CFW).			(d) Vent of Low-Carbon Stainless Steel (FXL).			(e) Vent of Austenitic Stainless Steel (FKE).	
3250	15.8	5.20	3670	16.6	5.16	16.6	5.70
3100	14.7	4.13	2650	11.3	3.83	11.4	3.77
2600	12.0	3.73	2200	9.6	3.01	9.6	2.03
2500	12.2	3.75	1650	6.9	2.11	6.9	1.65
2000	9.0	2.59	1000	3.8	0.28	3.8	0.58
1500	7.2	1.51	430	...	...	1.5	0.002
1000	4.1	0.61	3 at 430	1.5	0.01	...	...
500	1.6	0.003					
3 at 500	1.7	0.01					
$E = 4.0$			$E = 3.6$			$E = 3.9$	

TABLE XII.—*Effect of the Propellant on Erosion of Vents fitted to a Firing Vessel.*

Capacity of vessel, 66 cu. in. Diameter of vent, 2 mm.
 Vents of nickel-chromium steel (*GVR*), except where otherwise stated.

In this series the standard nickel and nickel-chromium steels gave $E = 5.2$ with cordite M.D. 2½ (results recorded below).

Charge. Grains.	Cordite M.D. 2½. Nickel Steel Vent (CFW).		Cordite M.D. 2½. Nickel-Chromium Steel Vent (CFX).		Cordite M.D. 2½ (950 cal.).	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.	Pressure. Tons per sq. in.	Loss of Weight. Grm.
3100	14.6	6.41	14.9	6.64	14.7	6.63
2500	11.55	4.86	11.6	4.74	11.3	4.97
2000	9.1	3.28	9.0	3.45	8.9	3.43
1500	6.75	1.98	6.7	1.99	6.7	2.24
1000	4.0	0.83	4.0	0.81	4.1	1.05
500	1.6	0.01	1.7	0.04	1.9	0.07
3 at 500	...	...	...	...	1.9	0.08
	E = 5.2		E = 5.2		E = 5.3	

Charge. Grains.	Charge B (880 cal.).		Charge. Grains.	Charge C (855 cal.).		Charge. Grains.	Charge D (830 cal.).		Charge. Grains.	Charge E (750 cal.).	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.		Pressure. Tons per sq. in.	Loss of Weight. Grm.		Pressure. Tons per sq. in.	Loss of Weight. Grm.		Pressure. Tons per sq. in.	Loss of Weight. Grm.
3250	15.8	6.03	3100	14.2	3.97	3250	15.2	4.45	3550	15.3	2.57
2440	11.0	4.22	2500	10.8	3.32	2440	10.8	3.27	2650	10.4	1.37
2010	9.0	3.32	2000	8.3	1.76	2010	8.6	2.76	2200	8.6	0.41
1500	6.5	2.34	1500	6.2	1.43	1500	6.5	1.70	1650	6.4	0.39
920	3.7	0.69	1000	3.8	0.31	920	3.6	0.60	1000	3.7	0.026
400	1.2	0.009	500	1.7	0.008	400	1.2	0.007	430	1.1	0.006
3 at 400	1.1	0.02	3 at 500	1.6	0.025	3 at 400	1.0	0.02	3 at 430	1.2	0.015
	E = 4.3		E = 3.6			E = 3.6			E = 2.1		

Charge. Grains.	Charge F (690 cal.).		Charge. Grains.	Charge G (675 cal.).		Charge. Grains.	Charge F (690 cal.).		Charge. Grains.	Charge G (675 cal.).	
	Pressure. Tons per sq. in.	Loss of Weight. Grm.		Pressure. Tons per sq. in.	Loss of Weight. Grm.		Pressure. Tons per sq. in.	Loss of Weight. Grm.		Pressure. Tons per sq. in.	Loss of Weight. Grm.
3500	15.2	2.37	15.3	2.53	3200	13.9	2.49	14.0	2.23		
2750	11.4	1.37	11.2	1.94	2600	10.5	1.23	10.6	1.90		
2300	9.3	1.21	9.2	1.27	2100	8.2	1.29	8.1	1.25		
1600	6.4	0.58	6.4	0.49	1600	6.1	0.60	6.0	0.46		
1200	4.3	0.29	4.3	0.23	1200	4.3	0.16	4.2	0.06		
850	2.9	0.02	2.9	0.015	700	2.2	0.007	2.3	0.007		
3 at 850	2.8	0.03	2.9	0.017	3 at 700	2.2	0.015	2.3	0.013		
	E = 2.0		E = 2.2			E = 2.2			E = 2.2		

The steels preserved the same order of erodibility under the action of different propellants, thus :

	Value of E .	
	Cordite M.D. (Table III.)	Charge E . (Table XI.)
Nickel-chromium steel (CFX)	4.5	1.9
Nickel-chromium-molybdenum steel (CNO)	4.4	2.1
Low-carbon stainless steel (FXL)	9.2	3.6
Austenitic stainless steel (FKE)	11.0	3.9

If T is the temperature of the gas and t that of the surface of the steel, the rate of transfer of heat is a function of $(T - t)$. It is shown by subsequent examination of the vents that the surface of the steel reaches its melting point. Suppose the temperature of the surface of the steel to be 1500°C ., then gas at 2900°C . (or 1400°C . above the temperature of the surface) would communicate to the steel about twice the amount of heat imparted by gas at 2200°C . (or 700°C . above the temperature of the surface). A ratio calculated in this way does, in fact, express the approximate relative erodibility of a given steel under the action of the different propellants used in the experiments.

TABLE XIII.—*Effect of the Nature of the Propellant on Erosion.*

Average value of the erosion figure for carbon, nickel, nickel-chromium, and nickel-chromium-molybdenum steels which all give similar figures with cordite M.D.

Propellant.	Calorific Value. Cal.	Estimated Approximate Temperature. $^{\circ}\text{C}$.	Average Value of E .
Cordite M.D. $2\frac{1}{4}$	950	2900	4.5 to 5.5
Cordite R.D.B. $2\frac{1}{4}$	930	2900	4.2
Charge A	912	2850	4.0
„ B	880	2750	4.2
„ C	855	2700	3.6
„ D	830	2600	3.6
N.C.T.	810	2500	3.1
Charge E	750	2300	2.0
„ F	690	2100	2.1
„ G	675	2050	2.2

The relative values of the erosion figure obtained with steels showing approximately equal erosion with cordite M.D. are given in Table XIII., together with the calorific value and estimated temperature of the propellant gases for a density of loading of 0.1 (equivalent to a charge of 1670 grains in a closed vessel of 66 cu. in. capacity).

The results clearly show that the lowering of the erosion figure (as measured by the loss of weight of vent plugs) produced by the use of cooler propellants is very much greater than any reduction which may be produced by changing the composition of the steels now used in gun construction.

Examination of Eroded Vent Plugs.

The form of the axial hole after erosion by the hot gases is of interest. Propellant gases at high pressure erode the edges at the entrance to the axial hole; then follows a relatively unaffected region, succeeded by one which has suffered most from the erosive action of the gas (Fig. 48, Plate XVII.).

As is well known, when a fluid such as water passes from a container of large diameter through an orifice, the convergent currents of water approaching the orifice cause a contraction of the issuing fluid (the *vena contracta*), so that instead of a parallel or cylindrical flow it becomes a stream of diminished breadth, the greatest contraction being at a point whose distance from the orifice is equal to half the diameter of the orifice, the diameter of the contracted stream being about 0.8 of that of the orifice. The characteristic form of the eroded vent is apparently due to an analogous cause.

When a low-pressure charge had been fired through a vent, an even more interesting effect was observed. The turbulence of the gases from a high-pressure charge was too great to reveal more than a single impingement of gas on the surface, but with smaller velocities of the outgoing gas several slight ridges were visible in the axial hole of the vent (Fig. 53, Plate XVIII.). These were apparently due to successive reflections of the issuing stream of gas from the surface. At intermediate positions there were protected regions where the steel suffered less erosion, thus giving rise to the succession of ridges.

The characteristic form assumed by eroded vents offers support to the idea that the initiation of scoring in guns may be largely due to the current of gas at the rear of the projectile, which, however, can to some extent be controlled by the design of the lead from chamber to rifling, and the relative diameters of chamber and bore.*

Some vents were made with a wide entrance channel and a narrower exit channel connected by a slope representing, in an exaggerated form, the chamber, slope and bore of a gun. Figs. 49 to 52 (Plate XVII.) show four such vents having the following dimensions :

Diameter of entrance channel . . .	10 mm.
" " exit channel . . .	5 mm.
Axial length of slope . . .	25, 10, 5, and 2·5 mm.
Angle of slope . . .	6°, 14°, 27°, and 45° respectively.

The increase in the amount of localised erosion (scoring) in the exit channel as the steepness of the slope increases is clearly shown. In order to measure the amount of erosion occurring at different positions, vents were made up in three parts, which could be unscrewed, and the erosion of the entrance, slope, and exit portions separately determined (Table XIV.). The erosion occurring in the entrance channel was approximately constant and small in amount; the loss of weight of the exit channel increased progressively as the slope connecting the two channels became steeper. The erosion of the central portion was affected by two variables, decrease of length and increase of angle, the former tending to reduce and the latter to increase the total loss of weight. Thus the loss of weight of the central portion first increased and then diminished again as the length of slope was reduced. The loss of weight per unit length of slope, however, increased regularly as the slope became steeper.

Although there can be no quantitative relation between the behaviour of a vent and that of a gun, the analogy indicates that an increased slope between chamber and rifling leads to increased localised erosion in the bore, and a steep slope may initiate severe scoring.

* Hugoniot and Sébert,⁽¹⁵⁾ Charbonnier,^(6, 7) Tulloch,⁽³³⁾ Bravetta,⁽⁴⁾ Earle,⁽¹³⁾ Secondo.⁽⁴¹⁾

TABLE XIV.—*Erosion Tests of Composite Vents of Nickel Gun Steel (CFW).*

Capacity of vessel, 66 cu. in. Diameter of vent : entrance, 15 mm. ;
 Charge, 1500 grains of cordite M.D. 2½ exit, 10 mm.
 (lot B). Length of slope, 2.5 to 25 mm.
 Pressure, 5.0 tons per sq. in.

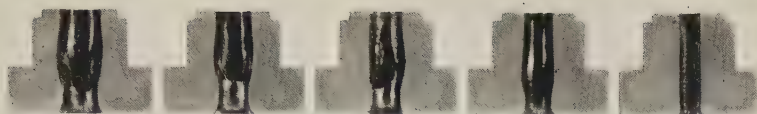
Description of Vent.	1 Charge.	5 Charges.	10 Charges.
	Loss of Weight. Grm.	Loss of Weight. Grm.	Loss of Weight. Grm.
Entrance : diam., 15 mm. ; length, 10 mm.	0.002	0.03	0.06
Slope : length, 25 mm. ; angle, 6°	0.08	0.32	0.57
Exit : diam., 10 mm. ; length, 30 mm.	0.11	0.53	1.17
Entrance : as above	0.001	0.04	0.06
Slope : length, 10 mm. ; angle, 14°	0.11	0.47	0.75
Exit : as above	0.29	1.40	2.68
Entrance : as above	0.002	0.02	0.06
Slope : length, 5 mm. ; angle, 27°	0.09	0.43	0.68
Exit : as above	0.30	1.71	3.29
Entrance : as above	0.004	0.03	0.09
Slope : length, 2.5 mm. ; angle, 45°	0.12	0.33	0.52
Exit : as above	0.45	1.76	3.40
Erosion of slope per 10 mm. of length :			
Angle 6°	0.03	0.13	0.23
14°	0.11	0.47	0.75
27°	0.18	0.86	1.36
45°	0.48	1.32	2.08

Microstructure.

Erosion vent plugs were sectioned axially and the cut faces polished for microscopical examination.

Non-Ferrous Metals and Alloys.—Intercrystalline cracks extending from the eroded surface into the metal were visible in all the vents through which the higher charges had been fired. Typical structures observed in nickel are shown in Fig. 56, and those in Monel metal in Fig. 57 (Plate XIX.).

It is most improbable that the development of intercrystalline cracks in the surface layers can be due to chemical action, owing to the extremely short time occupied by the passage of the hot



of charges. 20

15

10

5

1

Charge, 1,500 grains of cordite M.D. $2\frac{1}{4}$; pressure, 1st round, 6.3 tons per sq. in.,
diminishing as diameter of vent increased to 5.0 tons per sq. in.

FIG. 48.—Effect of firing through 5 mm. diam. vents. $\times 0.5$.

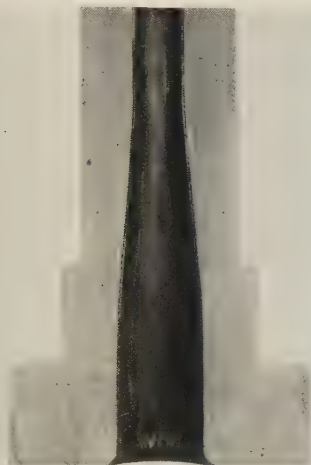


FIG. 49.—Slope 25 mm. long.

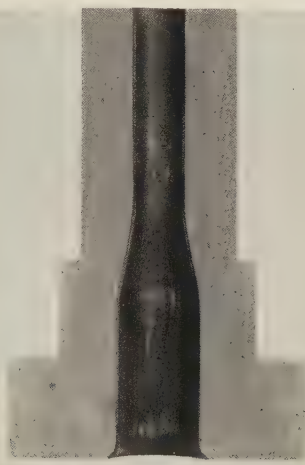


FIG. 50.—Slope 10 mm. long.

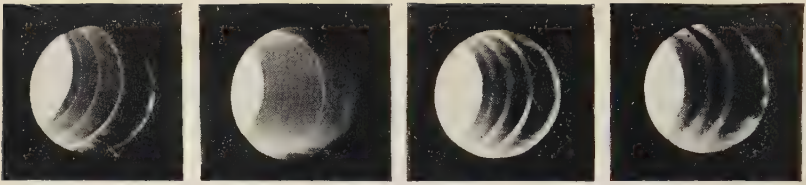


FIG. 51.—Slope 5 mm. long.



FIG. 52.—Slope 2.5 mm. long.

Figs. 49-52.—Half-sections of vents after firing 2,500 grains of cordite, M.D. $2\frac{1}{4}$
(pressure 10.6 tons per sq. in.), showing effect of slope in localising erosion.
Entrance 10 mm. diam.; exit 5 mm. diam. in each vent. (Actual size.)



1 charge

1 charge

5 charges

10 charges

Mild steel.

carbon gun steel.

Charge, 1,500 grains of cordite M.D. $2\frac{1}{4}$; pressure 5 tons per sq. in.

FIG. 53.—Effect of firing through a 10 mm. diam. vent. $\times 1.5$.

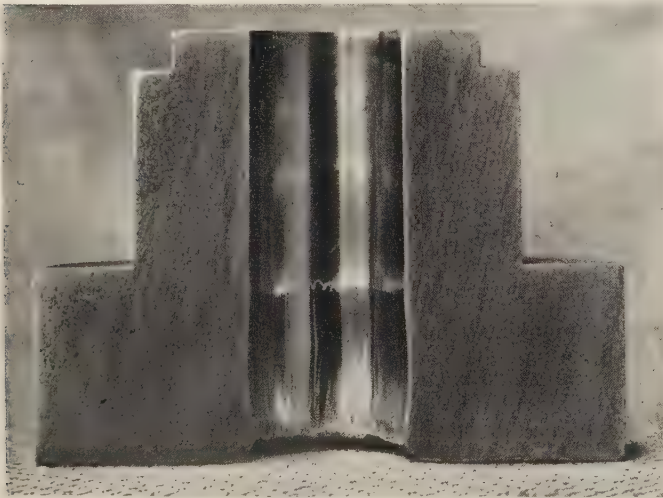


FIG. 54.—Effect of firing five charges (as above) through a nickel-steel vent. $\times 2$.



FIG. 55.—Appearance of surface of sectioned vent shown in Fig. 54. Direction of flow of gas upwards. $\times 30$.

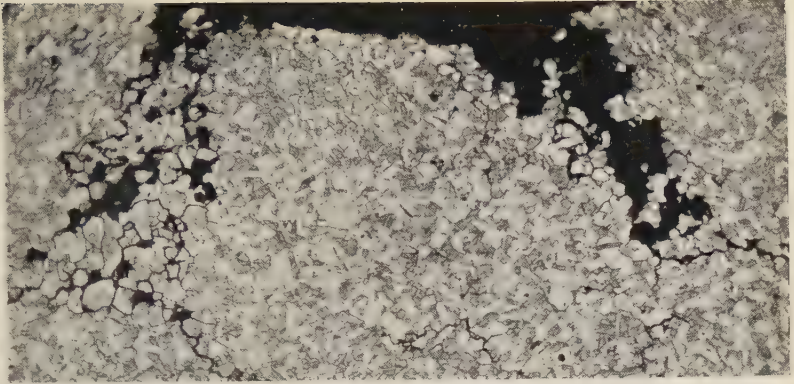


FIG. 56.—Nickel, showing intercrystalline cracks. $\times 50$.

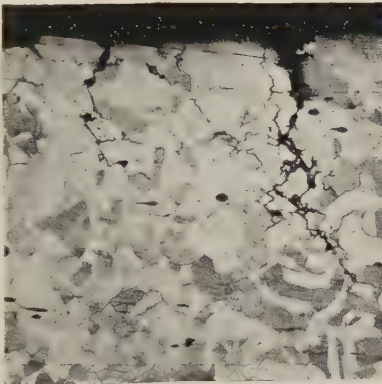


FIG. 57.—Monel Metal, showing intercrystalline cracks. $\times 100$.

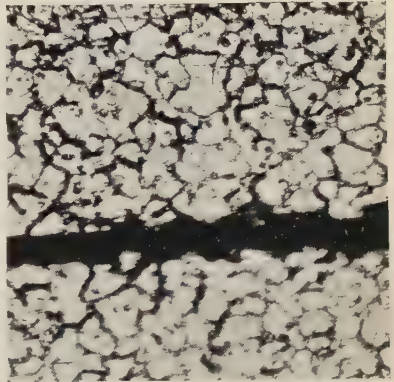


FIG. 58.—36.7 per cent. nickel steel (tangential section), showing intercrystalline cracks. $\times 100$.

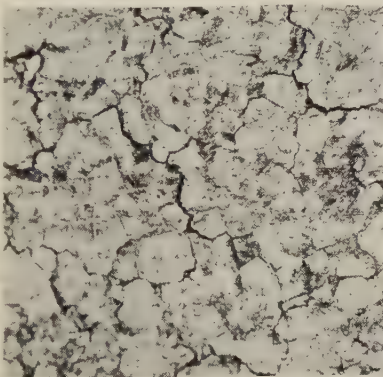


FIG. 59.—Nickel gun steel (tangential section), showing intercrystalline cracks. $\times 100$.

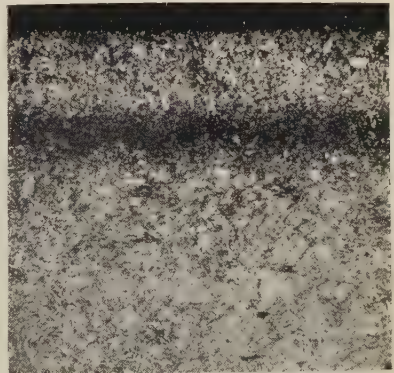
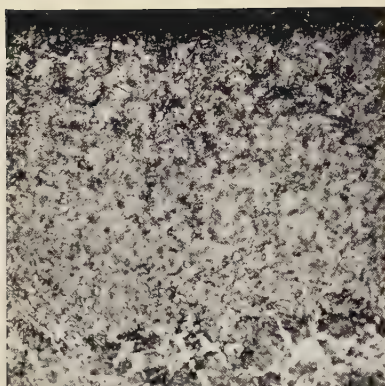


FIG. 60.—Nickel-chromium steel showing troostitic layer below skin after 3 rounds of charge *E* at a pressure of 1.44 tons per sq. in. $\times 100$.

Structure of eroded surfaces of vents. Propellant, cordite M.D. 2 $\frac{1}{4}$, except Fig. 60.



Carbon gun steel; depth of skin 0.016 in.
FIG. 61.— $\times 100$.

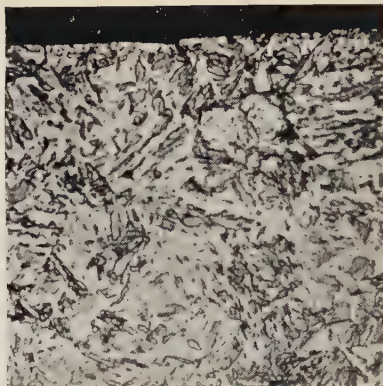
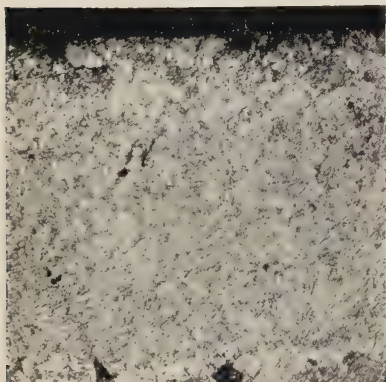


FIG. 62.— $\times 500$.



Nickel gun steel; depth of skin 0.016 in.
FIG. 63.— $\times 100$.

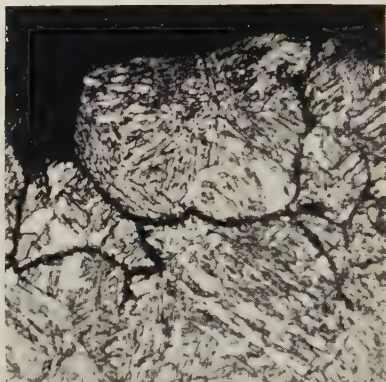
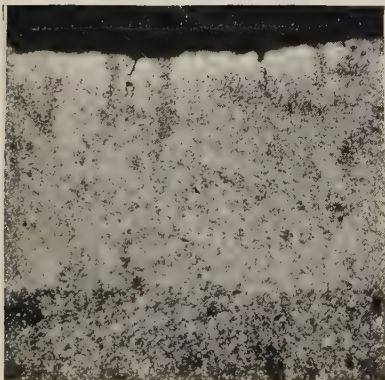


FIG. 64.— $\times 500$.



Stainless steel; depth of skin 0.012 in.
FIG. 65.— $\times 100$.

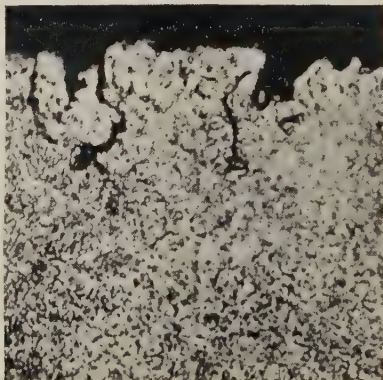


FIG. 66.— $\times 500$.

Hardened skins in vents. Propellant, cordite M.D. 2½. Pressure 15 tons per sq. in.

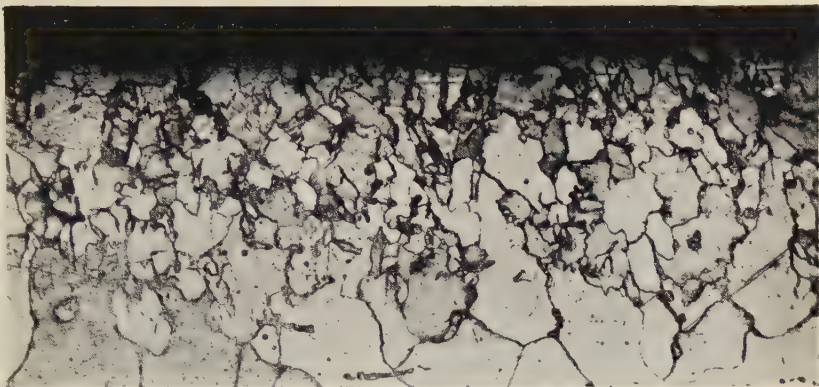


FIG. 67.—Armco iron. Depth of grain refinement 0.010 in. $\times 100$.

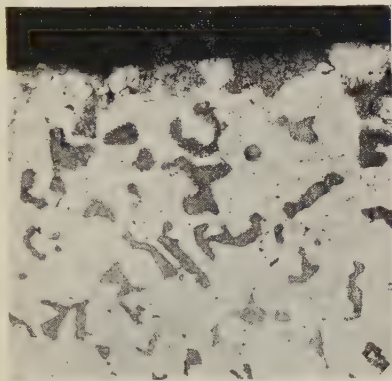


FIG. 68.— $\times 100$.

Mild steel, showing change of pearlite grain at surface to martensite, and accompanying crack.

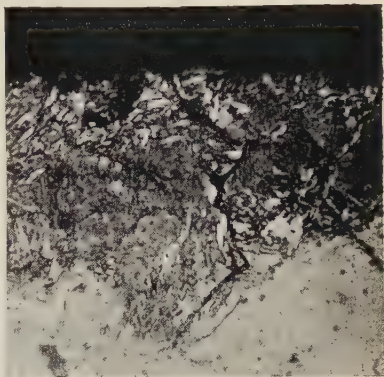


FIG. 69.— $\times 500$.

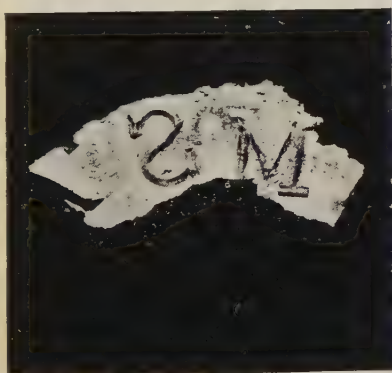


FIG. 70.—Fragment of steel detached from forward face of vent after firing; it had, while molten, taken the imprint of the letters "MS" stamped on the vent. $\times 5$.

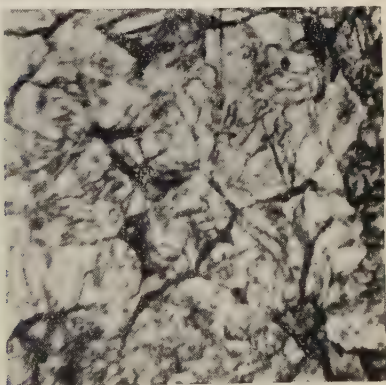


Fig. 71.—Nickel-chromium steel from the forward face of the vent after firing. $\times 1000$.



FIG. 72.—Structure of the material of the hardened skin of a 15-in. gun after normalising. $\times 250$.

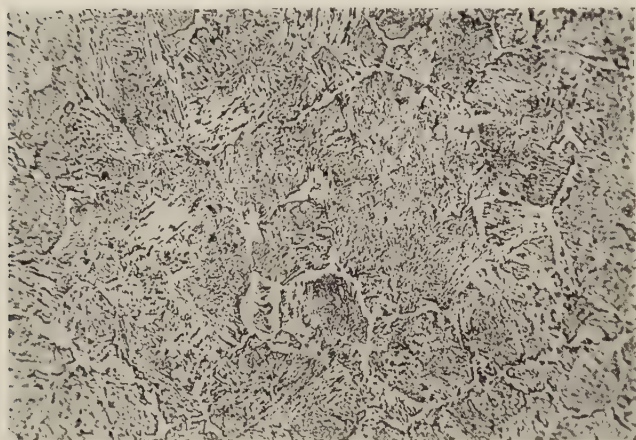


FIG. 73.—Structure of the material 0.1 in. below hardened skin of a 15-in. gun after normalising. $\times 250$.

(The specimens were wrapped in nickel foil, enclosed in copper foil, then heated to 900° C. and cooled in air.)

gases, nor are they directly dependent on a hardened skin, for no such skin is formed in non-ferrous materials. It appears, therefore, that these surface cracks are due to intercrystalline weakness at high temperatures, which results in cracking under the action of the circumferential stresses due to the pressure of the escaping gas.

Many of the austenitic steels showed similar pronounced intercrystalline cracks. Fig. 58 shows the surface cracking in the austenitic nickel steel.

Steel.—In all steels except mild steel and austenitic steels, a hardened skin was developed on the surface of the axial hole of the vent plug (Figs. 60 to 66, Plates XIX. and XX.). Unlike the cracks in non-ferrous materials, which were only developed by the higher charges, this hardened skin was produced by all charges. The formation of a hardened skin is the first change which takes place. It was distinctly evident, and in nickel gun steel attained a thickness of 0·015 in., when only one charge of cordite at a pressure of 1·5 tons per sq. in. had been fired, giving a loss of weight due to erosion of only 7 mg.

TABLE XV.—*Depth of Hardened Skin on the Surface of the Axial Hole of Vents.*

Propellant. Pressure in Firing Vessel. Tons per sq. in.	Cordite M.D. 2½.			Charge E.		
	2	4 to 11	15	2	4 to 11	15
Average for the ordinary gun steels	0·015	0·018	0·015	0·005	0·019	0·016
Stainless steel	0·006	0·011	0·009	0·007	0·013	0·010

The depth of skin formed in different steels is given in Table XV., in which it will be observed that the depth of skin increases with increase of pressure up to a point, and then diminishes again as the rate of removal of steel by erosion becomes very great. The skin formed in stainless steel is not so deep as in ordinary gun steels. This is an effect which follows from the lower thermal conductivity and from the higher critical range of stainless steel. The inner boundary of the hardened skin of carbon gun steel must at least have attained the temperature

of Ac_1 , or about $700^{\circ}C.$, but that of stainless steel must have reached $800^{\circ}C.$, since rapid chilling after exposure to a lower temperature would not produce hardening.

After the passage of gases from the higher charges, many of the steels showed surface cracking of an exactly similar type to that shown by non-ferrous metals (Figs. 58 and 59, Plate XIX.). These cracks are probably intercrystalline in every instance.

No difference in the character of the surface cracking or the hardened skin was discernible between annealed vent plugs and those in the oil-hardened and tempered condition. If a coarse ferrite network is present, however, it remains undissolved and persists in the hardened skin (Fig. 16, Plate IX.).

Mild Steel and Armco Iron.—Mild steel and Armco iron showed no hardened skin and very little surface cracking. The structure of mild steel shows a surface layer in which the pearlite grains are altered by mutual solution of the components of the pearlite, and a hardened spot is produced locally. Such spots at the surface of the axial hole often show cracks (Figs. 68 and 69, Plate XXI.). The altered layer is of the same depth as the hardened skin in ordinary gun steels.

The Armco iron was of interest in showing refining of the grain-size in the surface layer affected by the passage of the hot gases (Fig. 67). The fine structure extended to an average depth of 0.013 in., and the metal affected must have been heated at least to the upper limit of the critical range (Ac_3 , or $900^{\circ}C.$).

Evidence of the Molten Condition.—Examination of the vent often revealed the presence of a ridge of metal—or in some instances a thin layer—covering the lower part of the exit end of the vent plug. This layer was sometimes detachable, and was found to have taken an impression of machining or stamp-marks on the surface of the vent plug. Thus, Fig. 70 shows a flake of metal detached from the end of a mild steel vent, which clearly shows the letters "MS" with which the vent was stamped. Pressure was not acting on the vent at this position, and the only explanation of the behaviour of the steel is that molten metal was ejected through the vent hole, and that some of it trickled down and solidified on the outside of the vent plug. The conclusion that molten metal is removed is supported by the micro-structure of a number of these deposited particles or layers, all

of which showed structures consistent with the supposition that they had been cooled rapidly from the melting point (Fig. 71).

A 10-mm. diam. vent of nickel steel (*CFW*), through which five charges, each of 1500 grains of cordite M.D. 2 $\frac{1}{4}$, had been fired, showed evenly spaced ridges of metal along its length of the type shown in Fig. 53 (Plate XVIII.). In the sectioned vent the ridges showed an irregular edge, suggesting that a thin layer of the surface had been melted and swept forward by the rush of gas (Figs. 54 and 55).

Erodibility and Melting Point.

Pure metals melt at a constant temperature, but steels and alloys in general have a melting or freezing range of temperature within which the material is partially molten and offers practically no resistance to shearing stress. Table XVI. summarises information relating to several types of material examined in the erosion vent trials.

TABLE XVI.—*Erodibility and Melting Point.*

Material.	Relative Erodibility. (Table III.)	Melting Point. ° C.	Range below m.p. within which Melting begins. ° C.
Pure iron	< 4.0	1530	Nil
Carbon steel (0.16% C)	> 4.0	1500	30
Carbon steel (0.4% C)	4.5	1475	65
Nickel	7.0	1452	Nil
36% nickel steel	7.0	1457	10
Stainless steel	9.0	1490	Small
Austenitic steel	11.0	1450	"
Monel metal	13.0	1360	40
Copper	15.0	1084	Nil
70/30 brass	23.0	940	35

It indicates that the melting point is one of the fundamental factors governing the resistance of a material to gas erosion—a conclusion which is in agreement with those of other investigators who have carried out erosion vent experiments. Nickel and 36 per cent. nickel steel occupy an anomalous position in the table; judged by the melting point alone they should be at least as erodible as stainless steel. Erodibility is evidently not a function of the melting point alone. The latent heat of fusion,

the specific heat and thermal conductivity at high temperatures are bound to be of importance, although their exact values are unknown and their relative effects difficult to assess. The specific heat and thermal conductivity are similar to those of iron, but the high latent heat of fusion of nickel (73 cal. per grm. compared with 52 for iron *) would reduce the amount of nickel removed by melting, and the same probably holds for the 36 per cent. nickel steel. The values of these constants for all the ordinary steels are similar, and it seems probable that none of them has sufficient influence to override the importance of high melting point. The thermal conductivity of stainless steel is only about half that of carbon steel ; this would lead to a steeper temperature gradient and greater erosion. In the opposite direction the high thermal conductivity of copper (approximately 9 times that of nickel and iron) may help to account for the fact that its relative erodibility is less than would be expected from a consideration of the melting point only.

MECHANISM OF EROSION.

The Principal Action of the Gas in removing Metal in the Molten Condition, and its Subsidiary Effects in producing a Hardened Skin and Surface Cracking.

The life of a gun in relation to erosion by the hot gases generated by the propellant may be briefly summarised as follows :

In those parts of the bore in which erosion occurs a very thin layer of the surface is melted and swept forward by the rush of gas. Though the heating period is very brief, the steel immediately below the melted layer is heated above its critical range, and its constituents mutually dissolve to form a solid solution—austenite. The subsequent cooling of the hot layer by the conduction of heat to the mass of the tube is so rapid that the steel is caught in the martensitic or fully hardened condition. In the following round the same temperature cycle is repeated, and the surface layer is annealed, eroded, and re-hardened by the subsequent cooling. Thus the actual surface exposed to the gas is (after the first round) independent of the initial condition of the steel as regards heat treatment.

* "International Critical Tables," vol. ii. p. 458.

The cooling of the bore by conduction is accompanied by cracking induced by thermal contraction and constitutional volume changes which occur in the surface layer. In the lands, which possess greater rigidity in a longitudinal than in a transverse direction, the induced tensile stresses are mainly longitudinal, and therefore cracks running in a transverse direction predominate on their surfaces. The rigidity of the metal in the grooves is no greater in the longitudinal than in the transverse direction. The surface fissures in the grooves and in the chamber form a fairly uniform network, the longitudinal cracks becoming progressively more prominent under the action of the forward-moving gas.

The cracks usually extend to a greater depth than the hardened skin. The wedge action of copper, forced into the crack opened up by gas pressure, assists in extending the crack. The depth of cracking is greater in carbon steels than in alloy steels, which offer great resistance to the spread of a crack. Cracking may assist erosion and wear by presenting a roughened surface to the action of the hot gases, so promoting transfer of heat, and also by causing particles to flake off from the bore under the mechanical action of the rush of gas and under the abrasive action of the driving band.

At some stage in the life of the gun, scoring or severe localised erosion may set in. The initiation of this stage may be due to currents induced by the change of cross-section of the stream of gas on passing from chamber to bore, and by the presence of the projectile. Subsequently, scoring may be very rapidly developed by an actual escape of gas past the driving band. This may be due to imperfect centring of the projectile or, later in the life of the gun, to the presence of deeply scored channels which are not effectively sealed by the driving band. Scoring in well-designed high-power guns of large calibre is rare.

The Unimportance of Chemical Action.

It has been suggested that chemical action may play an important part in the erosion of guns; oxidation,* carburisation,† and nitrogenisation‡ have each been suggested as factors in erosion. Microscopical evidence is strongly against these theories,

* Fay,⁽¹³⁾

† Fay,⁽¹²⁾ de Sveshnikoff,⁽³¹⁾ Graziani,⁽⁴²⁾

‡ Fay,⁽¹²⁾ Wheeler,^(36, 37)

and there are really no grounds for supposing that chemical action can exert much influence on the progress of erosion by modern propellants.* Results of analyses of the surface of the bore are affected by the presence of material possibly containing carbon and nitrogen in the fine surface cracks, and arguments based on chemical analysis may be misleading. A hardened skin can be formed to a considerable depth in one round, and the time of contact with the hot gases is too short to allow the penetration of carbon or nitrogen to the full depth of the skin. Moreover, after annealing or normalising, the hardened skin shows a structure identical with that of the rest of the tube (Figs. 72 and 73, Plate XXII.).

An allied theory states that erosion is due to alternate solution under high pressure and temperature, and sudden release of the propellant gases, causing mechanical disruption of the surface of the bore.† It is known that iron or steel in a fine state of division can occlude a large amount of propellant gas under conditions obtaining in closed vessels (involving a much longer time of action of the gas than in a gun), but there is no evidence that the gas is released at atmospheric temperature in a manner likely to cause disruption of the surface. On the other hand, an appreciable time at a raised temperature is required to drive off the gas.‡

The evidence of experiments with vent plugs eroded by the passage of gas from a propellant fired in a firing vessel leads definitely to the view that the removal of metal from the bore of the vent takes place by melting, the molten metal being swept off the surface by the rush of gas. There seems to be every reason to consider that the same effects predominate in the erosion of a gun.

The Diminution of Importance of Frictional Wear as the Calibre Increases.

In addition to the action of gas, the frictional wear by the projectile is a factor which must not be overlooked in considering the life of a gun. The occurrence of metallic fouling in small arms and of coppering in guns points to a condition of "seizing"

* Howe,⁽¹³⁾ Piantanida.⁽²⁶⁾

† Klever.⁽¹⁸⁾

‡ T. C. Sutton and H. R. Ambler, "Abnormal Absorption of Gases by Steel," *Transactions of the Faraday Society*, 1926, vol. xxii. p. 406; *Journal of the Iron and Steel Institute*, 1926, No. II. p. 662.

between the bore and the bullet envelope or driving band during its passage down the bore. The conditions of high contact pressure, rapid acceleration, and absence of effective lubrication are such as to lead to severe frictional effects, which would be intensified by the roughening of the surface due to cracking of the hardened skin. The removal of metal from the bore by friction is indicated by the effect of material and design of bullet envelopes and of driving bands on the rate of wear of small-arm barrels and of gun tubes. In general, the frictional effect appears to be greatest in small arms; it is of some consequence also in guns of small and medium calibre, but it rapidly diminishes in proportion to the erosion due to gas action only as the calibre increases.

As an indication of the increased transfer of heat to the metal in large guns, it is significant that the thickness of the hardened skin is greater the larger the calibre. In a 16-in. gun it is nearly twice as thick as in a 12-in., while in the latter it is 4 or 5 times as thick as in an 18-pdr. gun (3·3-in.), and more than 10 times as thick as in a rifle or machine-gun barrel.

The time of action of the gas is longer the greater the calibre, and as, in addition, the ratio of weight of charge to surface of bore increases very rapidly with an increase of calibre, the flow of heat across the surface of the bore increases in a similar manner. On the other hand, the driving band thrust per sq. in. is similar for all guns. It is therefore likely that the proportion of the total erosion due to fusion of the surface (to resist which a high melting point is required), as opposed to mechanical action (to resist which strength is necessary), is greater in big guns than in guns of medium and small calibres. In a rifle or machine-gun the strength may thus be a more important factor than the melting point. Wear tests of Japanese infantry rifles reported by Okochi show that barrels of low-carbon steel (with the highest melting point) have a shorter life than those of alloy steels, which have better mechanical properties. A 13 per cent. chromium "stainless" steel of high tensile strength was found to give an unusually long life in a machine-gun during trials carried out by the Munitions Inventions Department in 1918.* Wear in a rifle or machine-gun,

* American experience with stainless steel rifle barrels is less promising than this isolated trial suggests; see H. O'Leary, "Stainless Steel in Small-Arms," *Army Ordnance*, 1928, vol. ix. p. 172.

therefore, does not follow the results of erosion vent experiments, and is probably less reliable than these as a guide to the rate of erosion in large guns. The relative lives of small guns which have fired cordite Mark I., cordite M.D., or N.C.T. (approximately 1 to 2·5 to 4), bear a closer correspondence to the behaviour of erosion vents fitted to closed vessels in which these propellants have been fired. It has, however, been found in these guns that extreme softness of the steel of the inner tube conduces to a short life. This is probably owing to the occurrence of abnormal expansion, since the rate of increase of diameter is greatest in the first stage in the life of such guns. Hence, mechanical strength of the tube, and especially strength of the built-up gun as a whole, cannot be disregarded, but it seems likely that, in a big gun, when the requisite strength has been ensured, further improvement of resistance to erosion of the inner tube can only be secured by the choice of material with a higher melting point.

CONCLUSIONS.

It seems most probable that the erosion occurring in large guns is almost wholly due to the melting and sweeping away of metal from the bore surface by the rapid stream of highly heated propellant gas. The amount of metal removed in this way is dependent on :

- (1) The nature of the propellant, the calibre and ballistics of the gun (which determine the weight of the charge, the temperature of the gas, the velocity of the stream, and the length of time during which erosive action persists), and
- (2) The physical properties of the metal—that is, its melting point, specific heat, latent heat of fusion, thermal conductivity, and characteristics of the metal surface affecting the rate of transfer of heat from gas to metal.

It will be noticed that surface cracking (though it is a condition which affects the rate of transfer of heat from gas to metal) is not specifically mentioned. It is considered that the surface cracking of steel due to heating and cooling through the critical range is not in itself a cause of erosion, and that erosion would not necessarily be reduced if such cracking were eliminated. The

indication of erosion vent experiments is that some kind of cracking is inevitable, and that if metals with no thermal critical points were employed intercrystalline cracking at high temperatures would still be likely to occur.

Of all the properties of the metal, the melting point appears to be the one having the greatest effect. Since the other physical properties are similar for all kinds of steel, it would appear that the property most essential in a gun steel to ensure high resistance to erosion is a high melting point.

Erosion vent experiments reveal Armco iron (that is, iron of the highest purity) as the material showing least erodibility. This confirms the general conclusions of several previous investigators in favour of mild steel, but the mechanical properties of such a material are unsuitable for withstanding the stress on the lands of a gun, and its use would almost certainly lead to choke of the bore and distortion of the lands. There is no metal or alloy of suitable mechanical properties for gun construction with a higher melting point than pure iron. Even if the mechanical properties of iron were suitable, the utmost advantage to be expected from its use is a reduction of erosion of about 10 per cent., which is small compared with that which should be attainable by the use of a cooler propellant.

Thus the use of a cooler propellant affords the only practicable method of reducing erosion. With any given propellant, however, the effects of erosion may be reduced to a minimum by attention to gun design, material, and building. This involves a correct design of the chamber, to avoid, as much as possible, the *vena contracta* effect, so minimising localised erosion near the commencement of rifling. Abnormal expansion of the tube or other deformation of the surface of the bore in the early stages of the life of the gun should be avoided by adequate strength and rigidity of the gun as a whole and by the use of a steel selected from among those giving a low figure of erodibility in erosion vent trials, but heat-treated to give a high yield point and good mechanical properties.

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- (2) P. R. ALGER : "Erosion and Ballistics," *Journal of the United States Artillery*, 1910, vol. xxxiv. p. 285; *Proceedings of the United States Naval Institute*, 1910, vol. xxxvi., Part II., pp. 697, 975.

(Opposes the theory of Vieille,⁽³⁵⁾ adopted by Yarnell,⁽³⁹⁾ that gun erosion is due to escape of gas past the driving band. Erosion is smooth wearing away of bore, due to intense heating of the surface and movement of gas over the surface.)

- (3) A. BENNINGTON : "Why Big Guns are Short Lived," *Scientific American*, 1920, vol. cxxii. p. 44. "The Death of a Big Gun," *Scientific American Monthly*, 1920, vol. i. p. 33.

- (4) E. BRAVETTA : "L'Erosione delle Artiglierie," *Rivista di Artiglieria e Genio*, 1911, vol. xxviii., Part III., July-Aug., p. 1.

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- (5) H. C. H. CARPENTER : "The Iron-Carbon Equilibrium Diagram and its Practical Usefulness," *Transactions of the Institution of Naval Architects*, 1918, vol. lx. p. 83.

- (6) P. CHARBONNIER : "Balistique Intérieure" (O. Doin, Paris, 1908), pp. 99 to 115.

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- (7) P. CHARBONNIER : "La Veine Gazeuse," *Mémorial de l'Artillerie Française*, 1922, vol. i. p. 1001.

(Reviews the *vena contracta* theory of erosion.)

- (8) C. CRANZ : "Lehrbuch der Ballistik," II., 1926, p. 155, and III., 1927, p. 185.

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- (9) W. CROZIER : "Report of the Chief of the Bureau of Ordnance, Washington," 1913.

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- (10) E. DEMENGE : "L'Érosion des Canons," *Revue générale des Sciences*, 1918, vol. xxix, p. 579.

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(Explains formation of hardened skin as due to heating of steel above A_c , and rapid chilling by cold metal below surface ; cold-work produced by rotation of the projectile said to increase tendency to form a martensitic layer.)

- (12) H. FAY : "The Cause of the White Layer," *Army Ordnance*, 1925, vol. v, p. 798.

(Formation of hardened layer accelerated by cold-work, and probably by absorption of carbon and of nitrogen.)

- (13) H. M. HOWE : "The Erosion of Guns," *Transactions of the American Institute of Mining Engineers*, 1918, vol. lviii, p. 513.

(Deals exhaustively with mechanism of erosion from a metallurgical point of view, but without disclosing a more resistant material than the ordinary gun steels. Least erosion found in 0.35 per cent. carbon steel, which gives a good combination of high m.p. and "white hardness." Properties conferring resistance to erosion are high thermal conductivity and high specific heat. See also discussions by R. Earle and H. Fay.)

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(The inner tube shows a hard skin, surface cracks, and continuous long fissures in the angles between the lands and the grooves ; a split is an extension of a surface fissure ; the formation of fissures is due to the presence of the hardened skin ; the hard skin is therefore considered to be the primary cause of splitting, and to avoid this a tube with lowest possible carbon content is recommended.)

- (15) HUGONOT and SÉBERT : "Étude des effets de la poudre dans un canon de 10 cm.," *Mémorial de l'Artillerie de la Marine*, 1882, vol. x.

(Importance of design of chamber ; develops theory of the *vena contracta* or *veine gazeuse*, the form of which depends (other factors being constant) on the relative diameters of bore and chamber.)

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(Discusses characteristics of erosion, mode of heat transfer ; effect of high temperature on the surface of the bore ; effect of full and reduced charges ; the remedy is a cooler propellant.)

- (17) H. J. JONES : " Characteristics of the Wear of Guns and Howitzers," *Journal of the Royal Artillery*, 1920, vol. xlv. p. 173.

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- (20) M. LÉTANG : " Sur l'usure des bouches à feu," *Mémorial de l'Artillerie Française*, 1922, vol. i. p. 1013.

(Remedy, cooler propellant and deposition on the bore of a metal which will not give a hardened skin.)

- (21) A. MALLOCK : " Report to Ordnance Committee, Woolwich," 1905.

(Erosion vent experiments with long conical vents. Erosion depends mainly on velocity and temperature of gas, only in a secondary degree on nature of steel.)

- (22) SIR ANDREW NOBLE : " Artillery and Explosives " (J. Murray, London, 1906), pp. 503, 536.

(Erosion dependent on heat of combustion, pressure and motion of gases, not on any chemical action. In forward part of chamber where gases are in rapid motion erosion is decided; in rear of chamber where temperature and pressure are highest and longest continued, but where there is little motion, there is no erosion.)

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(Regards erosion as due to : (1) chemical action (not a serious factor); (2) leakage of gas past driving band; (3) surface cracking (the most important factor); and (4) frictional wear of driving band.)

- (24) F. OSMOND : " Note sur la trempe superficielle de l'acier soumis à l'action des explosifs," *Mémorial des Poudres et Saltpêtres*, 1901, vol. xi. p. 211.

(Nature of the hardened skin.)

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(Progress of erosion is more rapid, the greater the charge, the higher the temperature, and the longer the time of action ; advantage of low-carbon steel in preventing spread of cracks.)

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- (35) P. VIEILLE : "Étude sur les phénomènes d'érosion produits par les explosifs," *Mémorial des Poudres et Salpêtres*, 1901, vol. xi. p. 157.

(Formation of surface cracks ; erosion due to penetration of surface cracks by gas leaking past driving bands (*fuites gazeuses*), leading ultimately to scoring ; erosion vent experiments showed resistance to erosion to be dependent on melting point ; iron and dead mild steel showed least erosion, the usual gun steels (nickel, chromium, and nickel-chromium) about 15 per cent. more, and 40 per cent. austenitic nickel steel a little less than twice that of pure iron. For translation, see (38).)

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- (37) H. E. WHEELER : "The Nitrogen Theory of Erosion," *Army Ordnance*, 1925, vol. v. p. 800.

(Attributes the altered surface layer to the action of nitrogen ; recommends use of steels containing chromium, which are stated to absorb nitrogen less readily.)

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(A translation of the work of Vieille.(35))

- (39) H. E. YARNELL : "Gun Erosion," *Journal of the American Society of Naval Engineers*, 1910, vol. xxii. p. 334 ; *Journal of United States Artillery*, 1910, vol. xxxiv. p. 181.

(Adopts Vieille's views on erosion ; gives results of erosion vent tests at Bethlehem Steelworks (wrought iron best, 20 per cent. nickel steel worst), and at Indian Head Naval Proving Ground (mild steel best ; increasing carbon or alloying with nickel, manganese, chromium, &c., increases erosion, and heat treatment has no effect.)

- (40) A. G. ZIMMERMANN : "Old and New Theories of Gun Erosion," *Army Ordnance*, 1925, vol. v. p. 801.

(Discusses theories ; erosion vent experiments, loss of weight of $3\frac{1}{2}$ per cent. nickel steel and chromium-vanadium steel approximately the same, that of stainless steel about 50 per cent. greater ; scoring attributed mainly to gas leakage.)

- (41) E. B. D. SECONDO : "Usura Delle Bocche da Fuoco," *Rivista Marittima*, 1927, vol. lx., Part IV., Nov., p. 307 ; Dec., p. 603.

(Effect of metal, propellant and design of chamber.)

- (42) M. GRAZIANI: "Alterazione dell' Acciaio dei Tubi d'Anima delle Bocche da Fuoco," *Rivista di Artiglieria e Genio*, 1928, vol. xlv., Part I., March, p. 404.

(Hardened skin due to carburisation by propellant gas.)

- (43) D. C. MCNAIR: "Erosion of Rifled Bores," *Army Ordnance*, 1928, vol. ix. p. 191.

(Discusses theories of erosion.)

Anonymous Publications.

- (a) "The Life and Power of Heavy Ordnance," *Engineering*, 1909, vol. lxxxviii. p. 123 ; 1910, vol. lxxxix. p. 486.

(Discussion of relative wear of German and English guns, and reference to work of Siwy.)

- (b) "Big Naval Guns," *Engineer*, 1913, vol. cxvi. p. 323.

(High erosion of cordite Mark I. ; dependence of erosion on calibre and weight of charge ; Noble's results.)

- (c) "Erosion of Guns," *Watertown Arsenal, Annual Report of Tests of Metals*, 1914, p. 208.

- (d) "The Examination of Rings from the Bore of a 10-in. Gun," *Watertown Arsenal, Annual Report of Tests of Metals*, 1916, p. 105 ; 1918, p. 245.

- (e) "Gun Erosion," *Engineering*, 1918, vol. cv. p. 640.

(Summary of work of Howe.)

DISCUSSION.

Colonel N. T. BELAIEW, C.B. (London), congratulated the authors on their very important piece of work. Many matters were exhaustively treated by the authors, and it was impossible, in a brief survey, to refer adequately to all of them. A very important one—and it seemed as if it appeared to the authors to be the corner-stone of their deductions—was their explanation that the most important factor contributing to erosion was neither the appearance of fissures and the subsequent cracking of the inner surface of the gun, nor the mechanical action of the gases, but the liquefaction of a certain surface layer and the consequent washing away by the hot gases of that surface layer. It seemed to him that it was still to be demonstrated that the same liquefaction, to the same extent, was to be observed in medium-sized and large calibre guns. He reminded the members that Sir W. C. Roberts-Austen had been of the opinion that there was no evidence of fusion.¹ As against that he would quote some words of Professor Tschernoff, who had made a life-long study of all questions appertaining to erosion. Tschernoff, in his paper "On the Erosion of the Bore in Steel Guns," said that "in small calibre guns and in machine-guns (in small arms) the heating of the inner surface of the bore was accomplished so quickly that the upper layer of the metal was heated above the melting temperature, and was literally washed away by the rushing gases." Thus Tschernoff described what he had observed in machine-guns and in small calibre guns in more or less the same words as the authors did. The only difference was that the authors believed that the melting always occurred in every gun. Tschernoff was of the opinion that such melting did occur in certain guns—in machine-guns and in guns of the smaller calibres. He (Colonel Belaiew) therefore asked the authors to state whether they were quite convinced that there was sufficient proof that liquefaction of that upper layer could be definitely shown in big calibre guns.

Tschernoff had been a member of the special Commission on the Erosion of Guns. He himself had also served on that Commission for several years. They had had before them extensive material; and they came to the conclusion that the heating above the melting point did not always occur. Tschernoff's view was that the first phase of erosion in any gun was the formation of a network of fissures caused by volume changes. He considered the barrel of a gun as an agglomeration of a large number of "elements" which were very rapidly heated and drastically cooled afterwards; he even called his theory a *physical geometrical theory*, because it was based on the volume changes.

¹ *Journal of the Iron and Steel Institute*, 1898, No. II. p. 235.

Tschernoff's opinion had further been that a gun barrel of any material—not necessarily of such a material that would undergo changes at the critical points—when subjected to that drastic heat treatment would always show that change of volume, and, as a result of such cyclical changes, fissures and subsequent cracks would appear. Only after that, in what he considered to be the second phase of erosion, did Tschernoff admit the importance of the mechanical action of gases in washing away some of the particles and in creating those large rows of longitudinal cracks, or, in some cases, the additional effect of melting.

With regard to the remedy, in the first instance Tschernoff stated that the most important remedy lay in the properties of the propellant. The Russian artillery were using propellants with a rather lower combustion temperature than Great Britain; nevertheless the temperature of those nitro-cellulose propellants had been high enough to cause grave apprehension, and Tschernoff had had to induce the chemical engineers to reduce the temperature of the combustion of the propellant and to discover propellants which would increase the life of a big gun by 20 or 30 per cent. So on that point, too, there was no difference of opinion between Tschernoff and his pupils (Generals Trophimov, Hermonius, and Krylov) and the authors of the present paper.

The authors took a rather gloomy view of the metallurgical possibilities of fighting erosion. They went so far as to say that there was no metallurgical remedy for the erosion of guns. That, of course, was quite in keeping with their theory. On the other hand, Tschernoff's theory, which attached great importance to the volume changes, did envisage the possibility of metallurgical remedies, because if once it were admitted that it was important for all those elements which were undergoing those drastic heatings and subsequent coolings not to develop very large fissures, it would be seen that a material with a high coefficient of expansion would stand better than a material which was not plastic, and from that point of view such metals as copper, nickel, and pure iron were much better. Therefore the same results at which the authors arrived on the basis of the latent heat and of the melting point would also be arrived at from the point of view of the mechanical properties of those materials.

In order to impress the importance of the metallurgical side—but always keeping it secondary in importance to the propellants—Tschernoff demonstrated the appearance of those cracks in every metallurgical operation which was more or less analogous to the action of gases in the gun; for instance, he always showed during his lectures hot-stamping stamps and dies which were covered by exactly the same fissures and cracks as a big gun. In order to impress upon his hearers the importance of producing material which would contract and expand in a certain way, he even showed specimens of clay which had been similarly affected by cracks as a result of the volume changes.

Therefore, whilst he (Colonel Belaiew) warmly congratulated the authors on their work, which he considered was one of the most

important contributions to the question, he would ask them, on the one hand, to produce more evidence of the appearance of liquefaction in barrels and guns, and, on the other, to show definitely that erosion did not generally start by a network of fissures and cracks but by the melting of the thin layer of the inner bore surface.

Professor T. TURNER (Member of Council) said that Colonel Belaiew had referred to the fact that cracks were produced in other cases similar in character to those mentioned by the authors. A common example in the trades in the Midlands was the steel dies used in hot-stamping. Those had often been brought under his notice, and he had conducted some experiments to follow up the production of those cracks and, as far as he could, to discover their cause. The base of the steel die was at a relatively low temperature. On the surface of the die was placed a piece of red-hot brass; it was certainly above the lower change point in steel. The hot brass was struck rapidly and then removed; an interval elapsed, and another piece was treated in the same way. There was therefore a constant repetition of temperature change. After some time small cracks began to develop in the steel, and they became deeper and deeper until at last a piece actually came away and the die became useless. Those cracks were very similar to those which were observed in guns; in fact, the photographs and microsections in the paper might very well pass for cracks in hot-stamping dies.

With reference to the erosion and the melting of a film of the metal, if the surface were first roughened in that way, it could be understood that not only would erosion take place, but the small particles might very rapidly fuse; he suggested that the fusion might be due, not to the taking off of a uniform layer, but to the taking off of particles which had already become roughened.

Dr. W. H. HATFIELD (Member of Council) remarked that he felt that the research described was extremely complete and that there was plenty of evidence for the authors' conclusions. He was glad to see the publication of the work, because it did put on a very firm basis for the future the prevalent views with regard to the matter. When one had in mind the conditions of temperature and of pressure—not forgetting the possibilities of chemical action—it was readily conceivable that the metal would be removed in the manner suggested by the authors. Looking at the problem in an empirical way, it was a fact that, whereas before the war and up to its early stages erosion had been regarded as a fundamentally important subject for people like himself who were engaged in research in that field, by the middle of the war they had been taught to regard the question of the erosion of guns as being of less importance than had previously been supposed, because during the war the life of gun tubes of a number of types had been found to be far greater than had been anticipated. That was a

statement of fact, and had a bearing upon what the authors had to say. It simply meant, to his mind, that since those gun tubes which had served so well had been, in a generic sense, made of the same material as those which, in particular cases, had not served so well, the cause of the drastic erosion which, in specific cases, had taken place was due to some other cause than the characteristics of the steel of which the gun tubes had been made, and the members had had put before them in a most concise way, with the support of excellent experimental evidence, the authors' explanation, which he had every confidence in accepting.

Dr. H. MOORE, O.B.E. (Research Department, Woolwich), said that his views were substantially identical with those of the authors; he wished, however, to emphasise one or two points. The subject of the erosion of guns had been the happy hunting ground of the speculative theorist for many years. Those who were familiar with the literature of the subject, or who had glanced through the bibliography at the end of the paper, would have noticed the remarkable variety and number of explanations of the mechanism of erosion. The chemical theories of nitrogenisation, of carburisation, of oxidation, and so on, had been based on what he thought was very thin evidence indeed. From some of the papers one might imagine that it was enough to provide an industrious metallographer with a piece of a worn-out gun, in order to obtain, in the course of a few weeks, a complete theory of erosion, and probably the remedy as well. It was hardly necessary to record that such remedies had proved quite illusory. The present paper was of an entirely different standard; it was based on many years of patient observation of the erosion of guns, which the authors had had peculiarly good opportunities of studying, and on a large amount of well-designed experimental work. The conclusions arrived at by the authors deserved far more serious consideration than the bulk of the papers already published on the subject.

He had mentioned a few of the more speculative theories of erosion, but there were two or three others which, perhaps, merited a little more attention. Erosion was accompanied by a number of curious and interesting phenomena—the formation of a hardened skin on the surface of the bore, the early development of a network of cracks in that hardened skin, and the penetration of the cracks below the hardened skin. The obvious thing was to consider that the hardened skin, and the cracks that developed in it, were to a large extent the cause of erosion. At Woolwich they had come to precisely the opposite conclusion—that those accompaniments of erosion had probably little or no effect on the development or progress of erosion. Personally he would go rather farther than Dr. Greaves in that respect; he doubted whether the fissures and the hardened skin really influenced erosion—the ordinary erosion which took place at a maximum at the commencement of rifling—to any appreciable extent.

One aspect of the matter which the authors had made very clear, but which he found confused a number of metallurgists with whom he had discussed the subject, related to the view that erosion was largely due to leakage of the gas past the driving band—between the driving band and the bore of the gun. That view had been developed some thirty years ago by Vieille, having been first suggested a good deal earlier by a previous worker, and it had been adopted by a number of writers on the subject since. The theory, that the main cause of erosion was leakage of gas between the driving band and the bore of the gun, was entirely untenable. Erosion was at a maximum at the commencement of rifling, and at that position, while the driving band was there, the pressure was so low that very little erosion would take place through the escape of gas at that pressure. Another point was that the driving band naturally sealed best on the lands of the gun, and the spaces which existed between the driving band and the bore of the gun were at a maximum in the grooves. That would naturally lead to the expectation that erosion caused by the escape of gas through those passages would be at a maximum in the grooves and at a minimum on the lands. But quite the opposite was the fact; the erosion was at a maximum on the lands and at a minimum in the grooves. Then, at the position reached by the driving band at maximum pressure, which, in different guns, might be anything between a distance of 3 and 12 calibres along the gun from the initial position of the projectile, there was comparatively little erosion compared with that which took place at the commencement of rifling, yet at that position—the position of maximum pressure in the gun—the spaces between the driving band and the bore were undoubtedly much greater than they were at the commencement of rifling, and the pressure was of such an order that the erosion ought to be enormously greater. Those considerations alone indicated that the erosion which wore out large high-power guns was not caused by leakage of gas past the driving band.

He considered that the authors had proved their conclusions as well as conclusions on such a problem could be proved. The difficulties of experiment on the subject were extremely great. A full-sized experiment was so costly as to be out of the question; for example, one could not take out the tube of a large gun and cut it up at stages to follow the progress of erosion. He thought that the evidence pointed so strongly to the conclusion that erosion consisted in the melting at each round of a thin layer on the surface of the bore and the removal of that thin melted layer by the rapid flow of hot gas, that that conclusion was bound now to be accepted.

Professor F. C. THOMPSON (Manchester) did not think that anybody could examine Table XVI. without realising that the authors had made out a very strong case for their theory. He thought, too, that the table was of interest in another connection. If he had understood him rightly, Colonel Belaiew had said that Tschernoff's view was that the

erosion was due, mainly at any rate, to the development of cracks as the result of heating and cooling. If that were the case, although all material on heating and cooling would be subjected to thermal stresses, and, therefore, would tend to crack, one would perhaps expect that the tendency would be greatest in a material which showed, in addition to the ordinary thermal effect, volume changes due to the critical points, and be less in the case of a material where the thermal effect only was operative. One could test that conclusion from Table XVI., since the authors had among their materials an "austenitic steel," and a 36 per cent. nickel steel, both of which fitted in well with the general melting-point/erodibility relation. The evidence, then, was certainly in favour of the authors' view of the origin of the erosion, rather than the view that it was due to the volume changes.

There was what seemed to him to be a critical way of differentiating between the two theories. The authors had shown that pure iron was the material which was most resistant to erosion of that type. If they determined the erosion of an ordinary gun steel by their vent test, and then plated on to the same material a layer, of appropriately small thickness, of electrolytic iron, heat-treating it if necessary to get it into a soft condition beforehand, and tested it, they would then have two identical vents, apart from the actual iron surface, and the volume changes, one would imagine, would be very much the same in each case.

CORRESPONDENCE.

Professor J. H. ANDREW (Glasgow) wrote expressing his conviction that the authors' explanation of their data was substantially correct. Their micrographs were extraordinarily good, and in every case seemed to bear out the construction put on them by the authors. He was particularly interested in the thin martensitic layer which formed even after the first firing of a gun, and he would appreciate the authors' comments on the following point. Was that martensite brought about by the quenching of a liquid layer? He thought it extremely probable, for it was difficult to imagine that in any section of the tube, heated momentarily above the Ac_1 by the sudden heat generated by the firing, the resulting structure would be martensitic. Limiting the argument to but one round of firing, the time during which any section of the tube was above the Ac_1 temperature would be too brief to allow of diffusion of carbon to be brought about. Whilst the α - γ transformation might be spontaneous, diffusion of carbon must require a definite time to take place, and would only be expected to arise provided the steel had been melted.

General E. HERMONIUS, K.C.M.G. (Plzen, Czechoslovakia), wrote that he had been studying the question of erosion for some thirty years. He started his researches at the Ijevsky Steelworks (in the Ural) on

guns worn out in service and sent to the works for remelting. Every gun was cut normally to the bore and also longitudinally, and its whole surface was carefully studied. The conclusion arrived at was that erosion had been due to a sweeping away of a thin layer of the inner surface of the bore by a whirlwind of hot gases driving forward the projectile and partly escaping past the driving band. The velocity of the gases must have been about 1000 m. per sec., their temperature from 2500° to 3000° C., and their density only $\frac{1}{8}$ or $\frac{1}{10}$ of that of water. It did not seem to be of material importance whether particles of the inner surface of the bore were washed off by the stream of gases before or after they began to melt, but, in point of fact, the writer considered it improbable that a whirlwind of such tremendous velocity and power would give a chance to many particles in its path to melt before tearing them off and carrying them away. The writer considered it most likely that torn-off particles would be melted down later on in the stream of hot gases, but he did not think that melting preceded the tearing action of the gases. Had melting of the inner surface of the bore occurred, there would always remain traces of it on the chamber or on the back of the projectile, but such occurrences had not been brought to the writer's knowledge. He (the writer) was not convinced that the vent experiments provided evidence of the molten condition; he thought that the letters shown in Fig. 70 could have been stamped just as well on red-hot metal.

He believed that the most important escape of gas occurred before the driving band of the projectile had been driven into the grooves; if that escape could be avoided the life of a gun would be doubled or trebled. After the driving band had filled in the grooves there still remained many cracks between the lands and the band, and they led to a further gas escape.

It seemed that the authors did not discriminate sufficiently between cracks of different nature and origin—that is, between the network of fissures covering the bore at the outset of erosion, and the more pronounced longitudinal cracks due to the mechanical action of the stream of gases. The theory of Professor Tschernoff attached importance to those two kinds of cracks and to the two corresponding stages of erosion.

Mr. T. H. WEBSTER (Glasgow) wrote: I think that the authors have made an important contribution to the knowledge of their subject. I myself saw some of the experiments on "erosion bolts" made by the late Sir Andrew Noble about the year 1910, and saw a 0.2-in. hole (the size he used in nearly all of the experiments) washed from 0.45 to 0.5 in. in one explosion. The *vena contracta* effect near to the commencement of the orifice—the diameter of 0.35 in. opened out into a chamber about 2 in. long with a diameter of about 0.5 in.; the diameter then successively contracted and opened out again—was most marked.

In his book "Modern War Methods," Schwarte gives a brief description of the German long-range gun used in the bombardment of Paris. It may be safely asserted that this gun was one of the most unusual so far manufactured, inasmuch as the volume of charge, 367 lb., was the largest ever used in a gun of its size, while the projectile weighed 220 lb.; also, the time that the projectile was in the bore was longer than for any other gun, because of the enormous velocity attained. Schwarte states that the ramming and volume of the chamber altered to such an extent from round to round that a corresponding increase in the charge was necessary to allow for the change in the density of loading, so as to produce as far as possible a constant muzzle velocity of 5250 ft. per sec. This shows that in the German long-range gun the erosion must have been very heavy near to the commencement of rifling, and tends further to verify the authors' conclusions, inasmuch as the intense heat generated by this large volume of gas rushing from the chamber and scrubbing over the slight corner at the commencement of rifling would melt the steel locally, and this would be accentuated by the length of time during which this operation was going on. It further tends to show that the gun did not become useless because of the high rubbing velocity of the steel projectiles on the steel gun near to the muzzle, but because of the excessive erosion near to the commencement of rifling. Schwarte's statements, together with the facts recorded by the authors, seem to prove that on all guns a long forward taper on the chamber is desirable.

The AUTHORS, in reply, stated that they were very pleased to have had a contribution from Colonel Belaiew because, on account of his work on the subject and of his close association with Professor Tschernoff, all the views which he expressed were worthy of serious consideration. Regarding Colonel Belaiew's question, they had to confess that they had not got direct proof that melting occurred in the sense that they could produce the molten metal. The whole thing was really an inference—they thought an entirely justifiable inference—from several lines of argument. The vent tests might be used not only to measure erodibility of a steel, but also to measure the erosive character of a propellant, so that one might get out a figure for the erosive character of various propellants. It was found that the life of larger guns (upwards of 4-in. or 6-in.), firing different propellants, was more or less inversely proportional to the erosive effect of the propellant as measured in a vent trial. There being a correspondence between the life of a gun and the erosive character of the propellant, it seemed likely that the conditions of the metal surface which were known to exist in the vents were also existent in the gun. There was the general inference also that if, as Professor Tschernoff believed, there was some melting in the smaller guns, then since it was certain that the heat effect in a bigger gun was very much greater in proportion to the surface exposed, all

the more was it to be supposed that there must be melting in the larger gun. Arguments of that kind had convinced the authors that the vent tests were really a good measure of erosion in the larger guns; they did not say in machine-guns, because frictional effects and mechanical properties came in more in those than in the big guns.

Professor Turner's remarks had been very welcome. There was, in the authors' opinion, only one way in which the surface cracking might contribute to erosion: it might affect the rate at which heat was absorbed on the surface. There might be a faster transfer of heat to a cracked than to an uncracked surface, with consequent quicker melting—which, they believed, Professor Turner suggested. They were glad to note that Dr. Hatfield had given them his general support. They agreed with Dr. Hatfield as to the present situation of the problem of erosion.

The authors were very grateful to Dr. Moore for his contribution, and more so for the constant advice which he had given them throughout the work. The work was really based on an investigation which had been in progress for many years before the authors joined the Research Department, Woolwich; it had just happened that Dr. Moore had not been able to carry it on, and had delegated it to themselves.

Professor Thompson's contribution was interesting, but the experiment which he suggested would not be conclusive. Professor Thompson had suggested the use of a composite vent, with a layer of iron. In that layer both the erosion and volume changes would take place. It would simply be a test on the iron layer at the bore. They thanked Professor Thompson for his comments on Table XVI., with which they agreed.

Professor Andrew's suggestion that the martensitic layer had been formed from steel in the molten condition was not borne out by observation. The metal on the surface which was actually molten was in all cases removed by the rush of gas. When ferrite was present in the structure, it persisted undissolved in the hardened skin (Figs. 10, 15, and 16). A similar heat effect on mild steel and on Armco iron caused a change in the surface layer which was consistent with heating above A_{c3} but not with melting (Figs. 67 and 68). Mutual solution of the ferrite and carbide in a pearlitic or sorbitic structure could apparently take place with great rapidity, giving martensite on cooling.

The authors were indebted to General Hermonius for his interesting comments. The evidence for melting was dealt with in the reply to Colonel Belaiew, but General Hermonius raised the further question as to whether melting actually occurred in an erosion vent test. The authors claimed to have direct evidence that melting did occur in the vents. The letters shown in Fig. 70 were not produced under pressure; the flake was detached from the lower wall of the free end of the vent, where the metal must have taken up its form solely under the action of gravity. The appearance of the vents (Fig. 55) supported the idea that melting had taken place. It was of frequent occurrence for metal

which had escaped being blown away to trickle over the lower forward end of the vent.

Objections to the theory that the main cause of erosion was leakage of gas past the driving band were put forward very clearly by Dr. Moore in his contribution to the discussion.

Colonel Belaiew and General Hermonius both held that volume changes and resulting cracking occurred in the steel as a condition precedent to erosion, while the authors held that such volume changes and their results were merely accompaniments of erosion. Measurements of the increase in diameter of 8-in. and 16-in. guns at short intervals proved conclusively that there was as much loss of material from the surface of the lands by erosion in the first 5 rounds as in the next 5 rounds, and that the loss per round remained constant for a considerable period of the life of the gun. In one instance in which more detailed examination was possible after 3 rounds, the hardened skin was fully developed, but the surface cracking was barely initiated, though the loss of steel per round from the surface had been normal for that type of gun. There was, therefore, no "network of fissures covering the bore at the outset of erosion" as General Hermonius suggested, because erosion started at the very first round. The formation of a network of fissures certainly preceded "scoring," a condition which the authors carefully distinguished from general erosion, and which they held could be avoided by efficient obturation and good design, material, and building.

The authors desired to thank Mr. Webster for drawing attention to a number of interesting facts which afforded support to the views they had expressed in their paper.

THE INFLUENCE OF PICKLING OPERATIONS ON THE PROPERTIES OF STEEL.*

By H. SUTTON, M.Sc. (FARNBOROUGH, HAMPSHIRE).

INTRODUCTION.

It has long been recognised that when steel is pickled it is liable to become brittle. Johnson⁽¹⁾ investigated the embrittlement of wrought iron and steel wires by pickling in acids or by treatment as the cathode in an electrolytic cell. The wires regained their ductility after standing for several days at the ordinary temperature, and more rapidly at elevated temperatures. Johnson attributed the embrittlement to the occlusion of hydrogen by the steel. Ledebur⁽²⁾ and more recent investigators arrived at the same conclusion.

Fuller⁽³⁾ showed that hydrogen readily penetrated iron at temperatures of 20° to 100° C., whether the iron were pickled directly in 1 per cent. sulphuric acid or were made the cathode in such acid. He explained his results by assuming that the initial penetration was due to the presence of atomic hydrogen, which subsequently associated within the metal to form molecular hydrogen. The pressure set up by the accumulation of the latter was suggested as the cause of the brittleness of pickled iron. Langdon and Grossman⁽⁴⁾ found that the ability of steel rods to withstand alternating stresses was reduced enormously by pickling in acids. Andrew⁽⁵⁾ studied the embrittling effect of caustic soda on iron, and Jones⁽⁶⁾ that of sodium and potassium salts.

Edwards⁽⁷⁾ has studied the influence of inclusions on the occurrence of blisters during the pickling of steel in acids, the passage of hydrogen through steel sheets during pickling, and the prevention of diffusion by electrolytic pickling and by means of oxidising agents.

Pfeil⁽⁸⁾ has recently made a valuable contribution to our knowledge on the subject of the influence of hydrogen on iron.

* Received January 10, 1929.

The effect of hydrogen on the tensile strength of the material used in his experiments was scarcely noticeable unless pickling were continued during the testing. Pfeil showed that the grain-size affected the tensile strength during pickling, and concluded that occluded hydrogen weakened the intercrystalline boundary.

The present paper describes experiments made with the object of adding to our incomplete knowledge of the effects of pickling and of methods of removing or of preventing the brittleness due to pickling.

EXPERIMENTS.

Experiments were made to ascertain the influence of pickling in acid solutions on several kinds of steel strip. In order to obtain conditions as far as possible comparable, all the steel strip employed was approximately 0.015 in. thick and 2.88 in. wide.

Steel Strip Materials Employed.—The mild steel strip was hot-rolled to 20 gauge (0.036 in.), normalised from 920° C., cooled in free air, and cold-rolled to 28 gauge (0.015 in.) without any intermediate heat treatment.

The medium-carbon steel strip was a coil of cold-rolled 28-gauge steel strip (0.015 in. thick), produced by a manufacturer.

The high-carbon steel strip was cold-rolled spring steel strip.

The alloy steel strip was of the high-tensile nickel-chrome steel type and had been heat-treated in the coil by the manufacturer. The compositions of the steels were as follows :

Steel.	Carbon. %	Silicon. %	Man- ganese. %	Sulphur. %	Phos- phorus. %	Nickel. %	Chromium %
Mild steel	0.11	0.12	0.39	0.04	0.05	Nil	Nil
Medium-carbon steel	0.46	0.18	0.62	0.04	0.02	"	"
High-carbon steel	0.85	0.09	0.66	0.02	0.02	Trace	"
Alloy steel	0.18	0.20	0.49	0.04	0.02	3.78	1.16

Preliminary Pickling Experiments.

Preliminary experiments showed that all the cold-rolled strips were embrittled seriously by pickling in 10 per cent. sulphuric acid solution (by volume) at all temperatures up to the boiling point. Both limiting-radius bend tests and "reverse" bend tests proved of value in ascertaining the embrittling effect, and it was decided to adopt these tests for the purpose. They are

described in an appendix. In recording the results, the mean value of four tests is quoted.

Following upon a number of further experiments it was decided to adopt the following conditions as standard for sulphuric acid pickling in this investigation: Greasy samples were cleaned with petrol before pickling; the pickle consisted of 10 per cent. sulphuric acid, A.R., (by volume), maintained at a temperature of 50° C.; 30 minutes' immersion was given; the samples were washed, brushed in running water, and dried on a cloth after removal. These conditions were adopted for the following reasons:

(a) Badly scaled specimens—for instance, normalised pieces—were cleaned effectively under these conditions.

(b) Longer periods of immersion, more concentrated acid, and higher or lower temperatures of the bath did not produce substantially greater degrees of brittleness in the pickled steels.

(c) Samples relatively free from scale did not suffer any very serious reduction of thickness by this treatment.

Pickling Experiments on Mild Steel Strip.

The influence of "standard" pickling was determined on samples of the cold-rolled material, untempered and after tempering at temperatures up to 600° C. It was found that bend tests on the strip showed a marked embrittling effect in the case of the cold-rolled material, and less embrittlement in the cold-rolled tempered strip (Fig. 1). Oil-hardening the strip from 920° C. had only a slight hardening effect. In order to obtain a harder condition, samples were water-quenched from a salt bath at 920° C. The influence of pickling was determined on the water-hardened strip and also on this material tempered at various temperatures (Fig. 2). The embrittling effect was, in general, much less than in the cold-rolled strip, and there was much less difference between longitudinal and transverse tests. The embrittling effect of pickling was very slight in normalised mild steel strip (cooled in air from 920° C.), and negligible in annealed strip (cooled slowly in the furnace from 900° C.).

No noticeable cracks were produced in any of the samples of mild steel strip by the pickling operations. Samples of the strip in the harder conditions were deformed slightly by bending, and

then pickled in order to detect any susceptibility to the formation of pickling cracks, but in no case was any discovered.

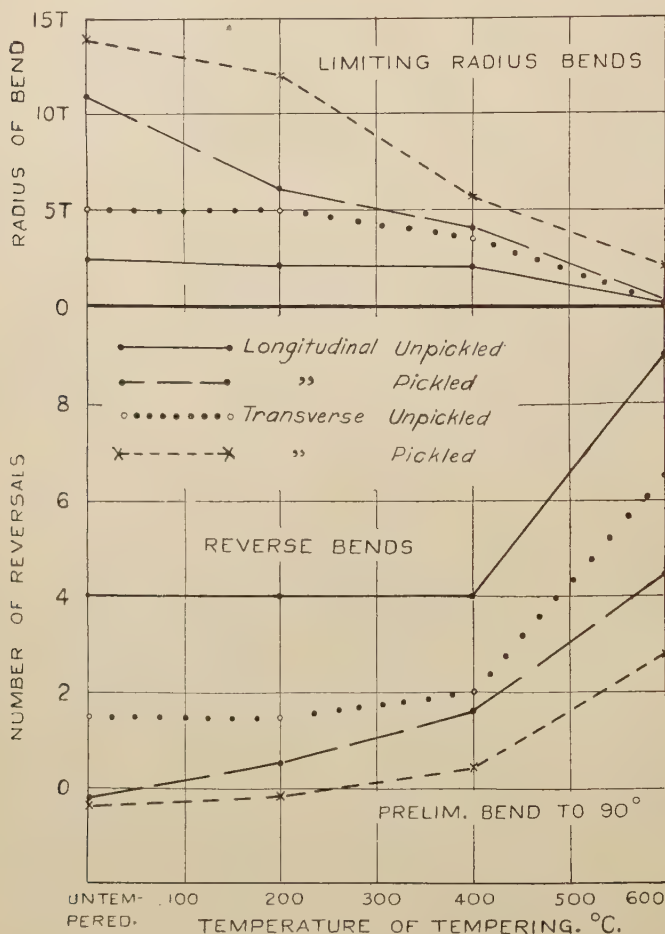


FIG. 1.

The brittleness of pickled samples of mild steel was found practically to disappear after standing for several days at the normal temperature, or after heating for periods of 30 min. at temperatures of 100° C. or higher. It was found, however, that the results obtained on the material which had been treated for

the recovery of the ductility were very slightly lower than those of the unpickled material. These observations on the recovery

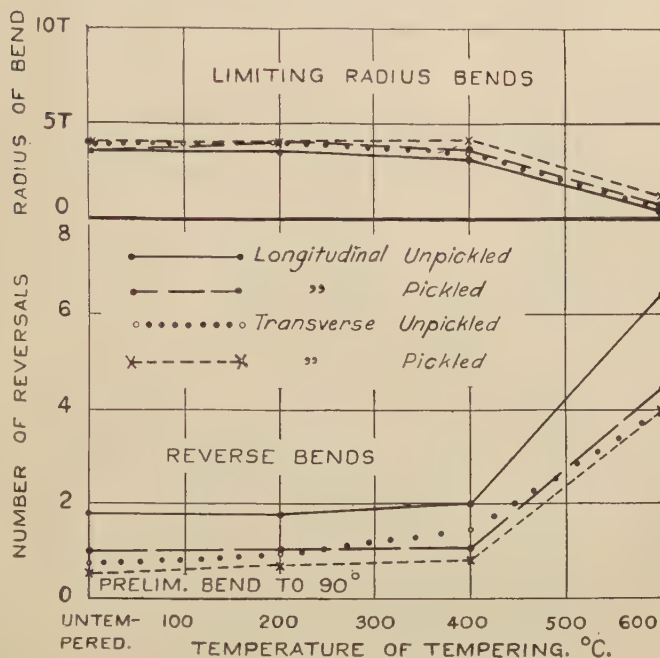


FIG. 2.

in pickled steels are in agreement with the results of Langdon and Grossman.⁽⁴⁾

Pickling Experiments on Medium-Carbon Steel Strip.

A relatively large amount of this material was available, and, as it was one on which more detailed information was desired, its investigation was carried out in greater detail than that of the mild steel strip.

As a first step, samples of the cold-rolled strip as received, others annealed by heating to 850° C. and cooling slowly in the furnace, and others normalised by heating in a muffle at 850° C. and cooling in free air, were pickled under the standardised conditions. The results obtained are recorded in Table I.

TABLE I.—*Influence of Pickling on Medium-Carbon Strip in the Cold-Rolled, Annealed, and Normalised Conditions.*

Condition.	Limiting Radius Bend.		Reverse Bend.	
	Longitudinal.	Transverse.	Longitudinal.	Transverse.
Cold-rolled { Unpickled . Pickled .	1T 8T	3T 15T	4.5 60° on P.B.	0.75 45° on P.B.
Annealed { Unpickled . Pickled .	0 0	0.5T 0.5T	9.0 9.0	4.5 3.5
Normalised { Unpickled . Pickled .	0 2.5T	1.5T 3.5T	6.5 2.75	3.5 1.0

P.B. = Preliminary bend.

The results obtained show that the cold-rolled strip "as received" is embrittled to a marked degree by pickling, that the normalised strip is embrittled slightly, and that the annealed strip is not embrittled appreciably.

As the normalised samples had a coating of scale before pickling, and in order to ascertain whether this had any influence on the result, further samples were normalised from a salt bath at 850° C. This treatment left only a very thin film on the surface. The results of tests on this material before and after pickling did not differ appreciably from those quoted above for the samples normalised after heating in the air-muffle.

A number of samples of the cold-rolled strip were tempered at various temperatures, and tested before and after pickling. The results of bend tests shown in Fig. 3 indicate that as the temperature of tempering was raised the embrittling effect of pickling tended to become less. The curves show a slight embrittling effect of tempering alone.

The results of bend tests on oil-hardened and tempered medium-carbon steel, pickled and unpickled, are given in Fig. 4. The progressive softening with an increase of tempering temperature, and the varying degree of embrittlement by pickling, in relation to the temperature at which the steel was originally tempered, are apparent.

Experiments were next made to determine the effect of

pickling on the tensile properties of the steel. The test-pieces were machined to the desired dimensions before heat treatment,

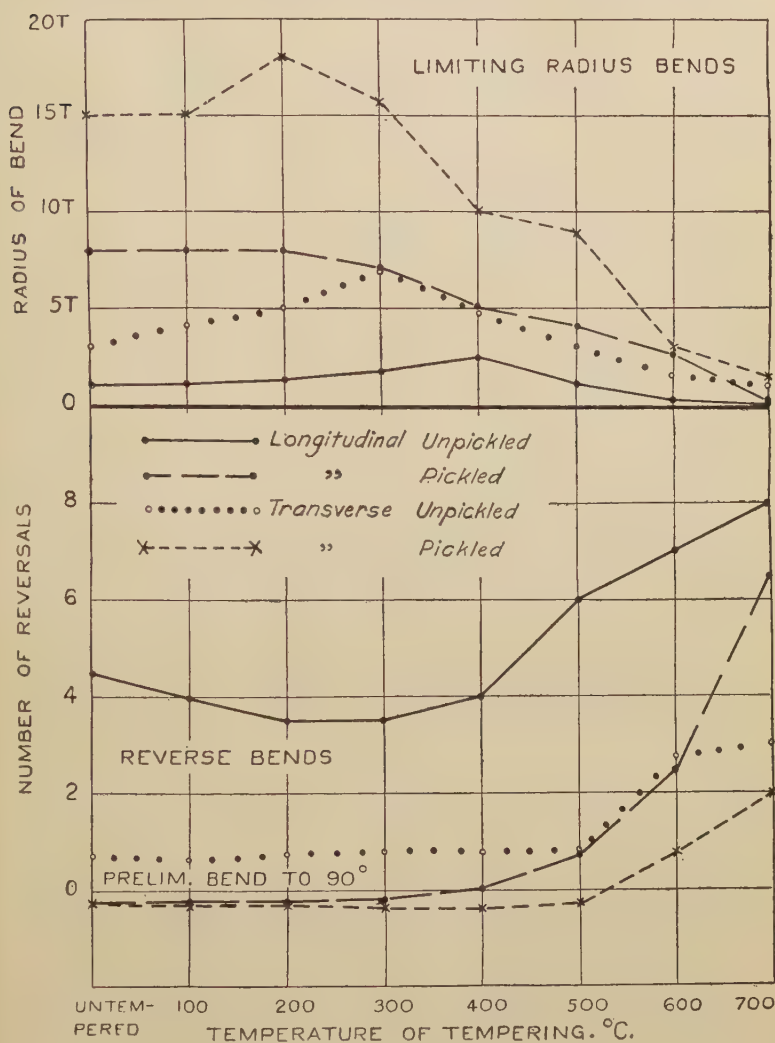


FIG. 3.

pickled, and tested immediately after pickling. Details of the tensile test are given in an appendix.

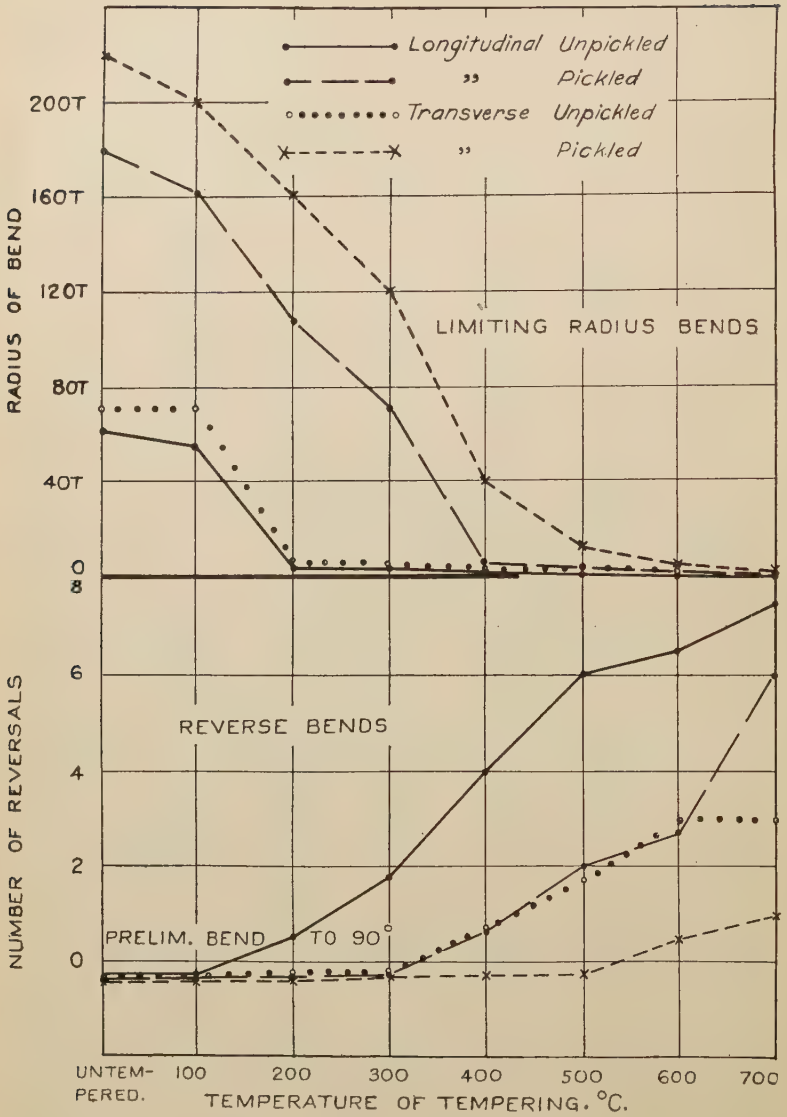


FIG. 4.

The results of tensile tests on the medium-carbon steel strip in the cold-rolled, and cold-rolled and tempered conditions, together with those obtained after pickling, are given in Table II. As

TABLE II.—*Tensile Tests on Medium-Carbon Steel Strip in the Cold-Rolled, and Cold-Rolled and Tempered Conditions, before and after Pickling.*

Sample (Longitudinal).	Limit of Proportionality. Tons per sq. in.	0.1% Proof Stress. Tons per sq. in.	Yield Stress. Tons per sq. in.	Ultimate Stress. Tons per sq. in.	Young's Modulus, <i>E</i> . Tons per sq. in. $\times 10^{-3}$.	Elongation—	
						On Fracture. %	On Parallel. %
Untempered	...	...	58.6	62.5	...	4.2	1.0
„ pickled	18.15	46.2	58.1	61.3	12.03	4.3	1.4
„ unpickled	17.96	45.6	58.4	61.7	12.10	5.2	1.4
„ „	...	...	59.4	62.4	...	5.6	1.8
Tempered at 200° C., {	...	...	59.2	62.9	...	5.7	1.8
unpickled	26.9	53.5	61.4	65.1	12.9	3.4	3.2
Tempered at 400° C., {	43.5	57.0	57.0	63.2	12.8	8.0	4.6
unpickled	44.3	57.0	57.2	63.0	13.5	7.3	4.5
Tempered at 600° C., {	...	...	41.4	47.1	...	12.2	7.1
unpickled	24.9	37.5	38.5	43.9	12.7	17.5	10.6

indicated by the results, pickling has no marked effect on the tensile properties of the cold-rolled medium-carbon strip.

Tensile tests were also made on the oil-hardened material, untempered, and tempered at various temperatures, unpickled and pickled. The results, given in Table III., revealed a substantial reduction in the tensile strength of the oil-hardened strip by pickling. In the oil-hardened and tempered material, as the temperature of tempering was raised the reduction in tensile strength due to pickling became progressively smaller until it disappeared completely.

Immersion in boiling water for half an hour apparently restored the tensile strength of oil-hardened pickled samples to the normal, and standing in air for two days effected almost complete restoration. It is of interest to note that although the tensile test does not reveal any marked influence of pickling on the material oil-hardened and tempered at 400° C., or at higher temperatures, definite embrittling effects of pickling were shown

TABLE III.—*Tensile Tests on Oil-Hardened and Tempered Medium-Carbon Steel Strip, before and after Pickling. (Longitudinal Samples.)*

Treatment.	Limit of Proportionality. Tons per sq. in.	0.1% Proof Stress. Tons per sq. in.	Yield Stress. Tons per sq. in.	Ultimate Stress. Tons per sq. in.	Young's Modulus, <i>E</i> . Tons per sq. in. $\times 10^{-3}$.	Elongation—	
						On Fracture. %	On Parallel. %
O.-H. 850° C., unpickled {	34.4	...	...	121.2	13.05	...	...
...	...	...	...	122.0	...	...	...
O.-H. 850° C., pickled {	...	...	...	38.6	13.1	...	...
...	...	...	...	38.4	13.4	...	...
O.-H. 850° C., pickled and immersed in boiling water 30 min. {	...	...	...	121.6	...	...	...
...	...	...	...	124.3	...	...	...
O.-H. 850° C., pickled and allowed to stand 48 hr. at room temperature {	...	...	...	114.7	...	...	...
...	...	...	...	109.5	...	...	...
O.-H. 850° C., T. 200° C., unpickled {	56.5	...	...	120.0	12.8	...	...
...	...	...	...	130.0	...	...	...
O.-H. 850° C., T. 200° C., pickled {	...	...	...	55.7	12.7	...	...
...	...	...	...	64.9	...	...	...
O.-H. 850° C., T. 400° C., unpickled {	56.1	81.7	...	86.5	13.4	6.0	1.0
...	...	...	...	89.5	...	...	...
O.-H. 850° C., T. 400° C., pickled {	61.3	...	...	86.0	13.2	...	...
...	...	...	...	89.3	...	...	...
O.-H. 850° C., T. 600° C., unpickled {	24.5	44.6	44.6	48.0	12.8	12.0	8.0
...	...	...	44.8	48.0	...	14.0	8.0
O.-H. 850° C., T. 600° C., pickled {	27.7	43.7	43.7	50.1	12.4	12.0	7.0
...	...	...	46.6	51.0	...	10.0	7.0

O.-H. = oil-hardened ; T. = tempered.

by bend tests on samples tempered at as high a temperature as 700° C. after oil-hardening (see Fig. 4).

A few bend test experiments were made to ascertain the loss of brittleness of pickled medium-carbon steel. The samples used were oil-hardened from 850° C., and tempered at 300° C., in which condition the embrittling effect of pickling is considerable. After pickling, the bend tests were made at intervals of time. Samples standing in the laboratory recovered rather more slowly than others exposed to the open air, but, in general, the maximum recovery was attained in 4 to 5 days. The results are reproduced in Fig. 5. Heating to 100° C. effected maximum recovery in

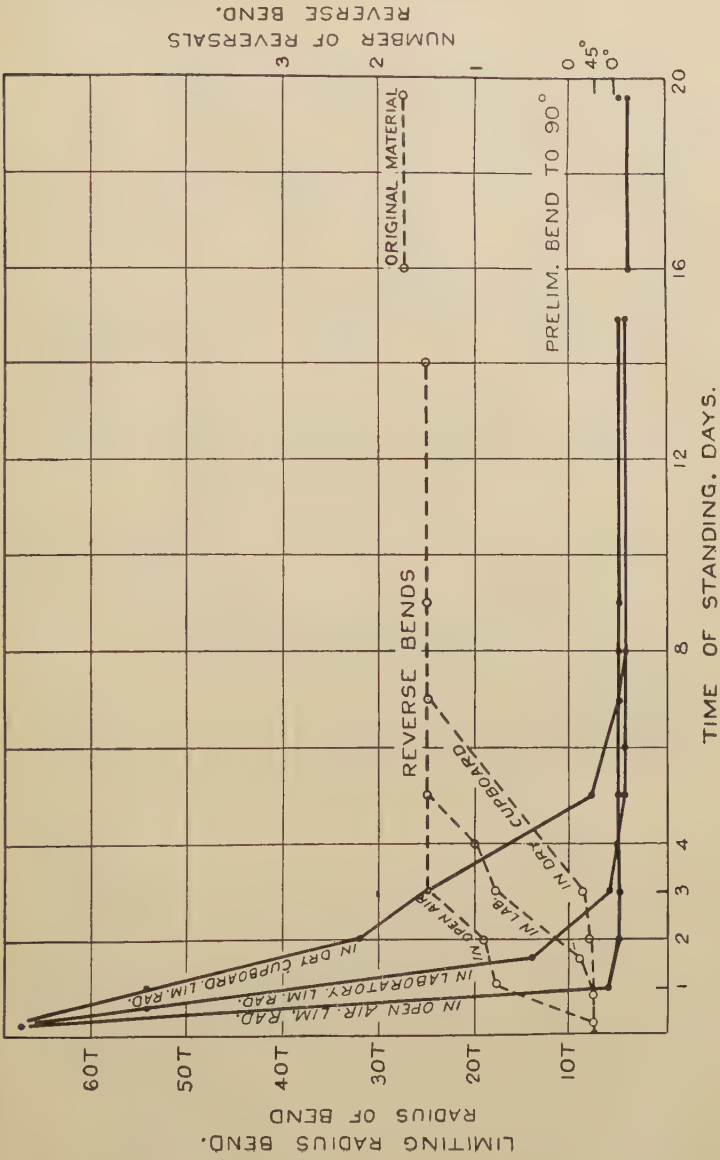


FIG. 5.

about 30 min., immersion in boiling water resulting in slightly more rapid recovery than heating in air.

Pickling Experiments on High-Carbon Steel Strip.

Samples of the cold-rolled material, untempered and tempered at 200°, 400°, and 600° C., were pickled, and together with unpickled samples of each kind were immediately submitted to bend

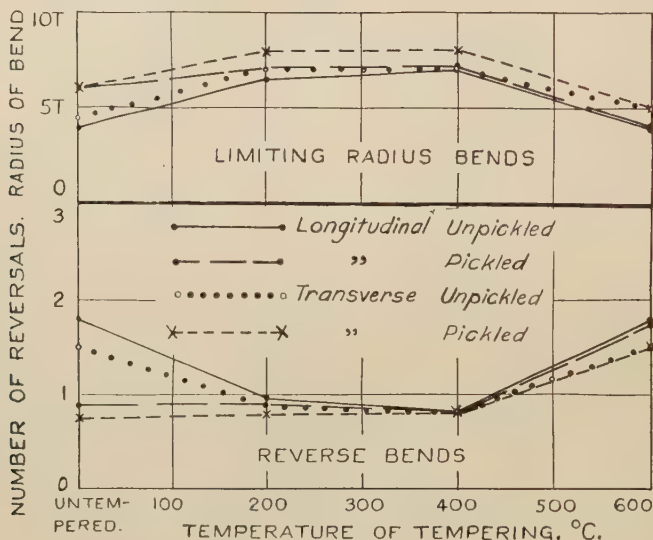


FIG. 6.

tests. The embrittling effect of pickling was most marked in the untempered material. Tempering alone at temperatures in the range 200° to 400° C. had a marked embrittling effect. The results of the bend tests are given in Fig. 6.

The results of bend tests on oil-hardened and tempered samples, pickled and unpickled, are given in Fig. 7. The pickled samples were all embrittled, but the embrittling effect was not so pronounced as it was in the oil-hardened and tempered medium-carbon steel. Corresponding longitudinal and transverse bend tests gave very nearly the same results. The reverse bend was not so valuable in the tests on this material, as the ductility of

samples tempered below 600°C. was insufficient to withstand one reversal. Samples of the high-carbon steel normalised from

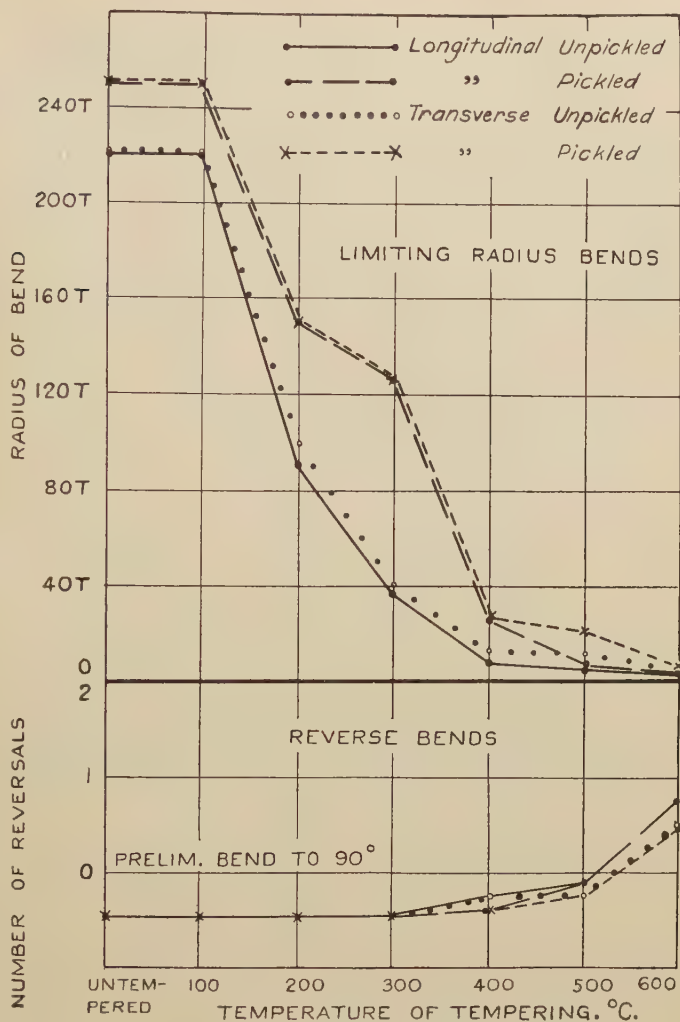


Fig. 7.

820°C. and others annealed at 800°C. were submitted to bend tests before and after pickling. The normalised samples showed

only a slight embrittling effect of pickling, and the annealed samples were only influenced appreciably in the reverse bend test.

Pickling Experiments on High-Tensile Alloy Steel Strip.

The high-tensile alloy steel strip, as received, had the following properties : Limit of proportionality, 38 tons per sq. in. ; 0.1 per

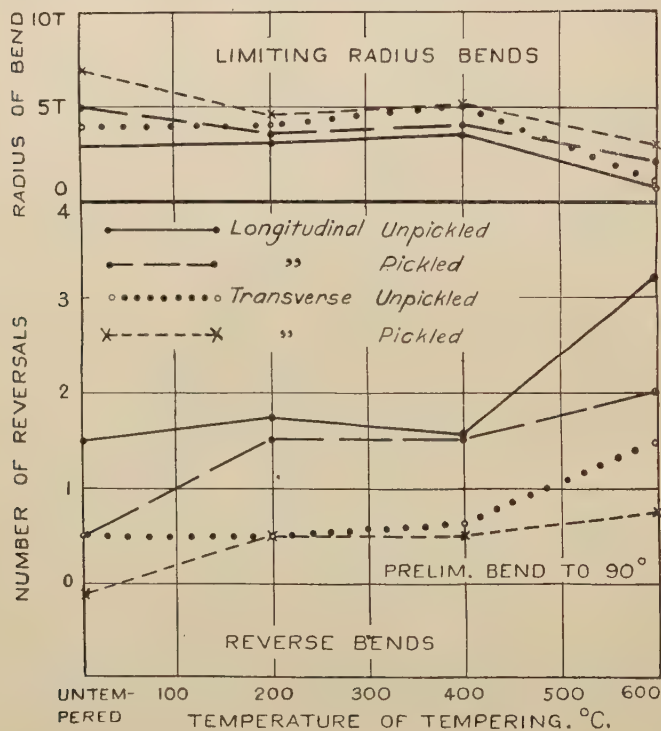


FIG. 8.

cent. proof stress, 63 tons per sq. in. ; and ultimate stress, 85 tons per sq. in. approximately.

Bend tests were made on the alloy steel strip as received and after pickling. The bend tests on the pickled strip gave very slightly better results than those on the unpickled material. The results for samples taken from different parts of the strip

varied slightly, but in all cases the results obtained on pickled material were equal to or better than those obtained on unpickled material.

A number of samples were oil-hardened from 860° C., and tempered at 200°, 400°, and 600° C. The results of bend tests on pickled and unpickled samples are given in Fig. 8. The embrittling effect observed was slight compared with that of the medium-carbon steel similarly heat-treated. A number of tensile tests were made on heat-treated samples in the pickled and unpickled conditions; the results are given in Table IV. Tests on the pickled samples were made immediately after pickling.

TABLE IV.—*Tensile Tests on Oil-Hardened and Tempered Alloy Steel Strip, before and after Pickling. (Longitudinal Samples.)*

Treatment.	Limit of Proportionality. Tons per sq. in.	0.1% Proof Stress. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Young's Modulus, <i>E</i> . Tons per sq. in. × 10 ⁻³ .	Elongation—	
					On Fracture. %	On Parallel. %
O.-H. 850° C., unpickled . {	30.6	58.7	101.0	13.5	...	...
	28.6	62.3	100.0	13.5	...	...
O.-H. 850° C., pickled . . {	25.5	59.3	95.2	12.6	...	...
	...	...	95.9	...	...	...
O.-H. 850° C., T. 200° C., unpickled {	45.9	73.7	91.9	12.0	6.1	1.6
	51.0	77.1	97.2	12.7	5.4	3.7
O.-H. 850° C., T. 200° C., pickled {	55.9	76.4	96.0	12.0	7.0	4.8
	53.8	78.0	97.9	12.5	8.0	3.9
O.-H. 850° C., T. 400° C., unpickled {	50.2	68.7	75.9	12.70	3.4	1.0
	51.4	73.0	79.0	12.94	3.5	2.0
O.-H. 850° C., T. 400° C., pickled {	...	...	81.0	...	5.1	2.8
	56.5	73.4	79.5	12.75	6.7	3.2
O.-H. 850° C., T. 600° C., unpickled {	44.5	55.7	57.5	12.3	...	2.0
	44.4	57.3	61.6	12.6	8.0	6.0
O.-H. 850° C., T. 600° C., pickled {	44.7	59.5	63.4	12.9	10.2	6.1
	44.0	55.3	62.3	12.8	11.4	5.8
O.-H. 850° C., pickled and immersed in boiling water for 30 min. {	33.1	66.2	97.7	12.4	...	...
	34.6	65.1	98.2	12.1	...	...
	31.9	62.5	95.7	12.3	...	...

O.-H. = oil-hardened; T. = tempered.

Although the tensile strength was not influenced in general, that of the untempered samples was reduced slightly by pickling.

The limit of proportionality stress was not influenced appreciably by pickling, but the elongation was increased slightly. The tensile strength of pickled, oil-hardened material recovered to some extent on immersion in boiling water for half an hour.

The results indicate that the nickel and chromium present, along with the relatively low carbon content, had reduced the susceptibility of the steel to embrittlement and other injurious effects of pickling.

Pickling Cracks.

At an early stage of the work it was found that if the medium- and high-carbon steels, hardened, and tempered in the lower range of temperatures employed, were subjected to deformation in that condition, they were liable to develop cracks during subsequent pickling at the places where deformation had occurred.

Samples of medium-carbon steel strip oil-hardened from 850° C., and tempered at 100°, 200°, or 300° C., or untempered, cracked on pickling at places where the metal had, after heat treatment, been either cut with shears or stamped for identification. To obtain further information, samples of heat-treated material were bent and then pickled; after pickling, cracks were noticeable at and along the bend. Some of the pieces fractured during pickling. In order to establish that the cracks were not due to bending alone, several severely bent samples were annealed and then pickled; none of these samples showed cracks after pickling. Typical pickling cracks are illustrated in Fig. 9 (Plate XXIII.).

The radius of bending did not appear to influence the result, nor did the angle of bend. When the angle of bend was very small and the radius relatively large, cracks still occurred in material heat-treated in the range indicated above. Hence it would appear that a very small amount of deformation in material of this kind is sufficient to cause cracking during pickling. Pickling cracks have not been observed in this steel in the cold-rolled condition, even after very severe deformation.

Samples of mild steel strip in all the conditions mentioned earlier were subjected to various treatments and examined for their susceptibility to pickling cracks. In no case was any observed.

FIG. 9.—Typical pickling cracks.

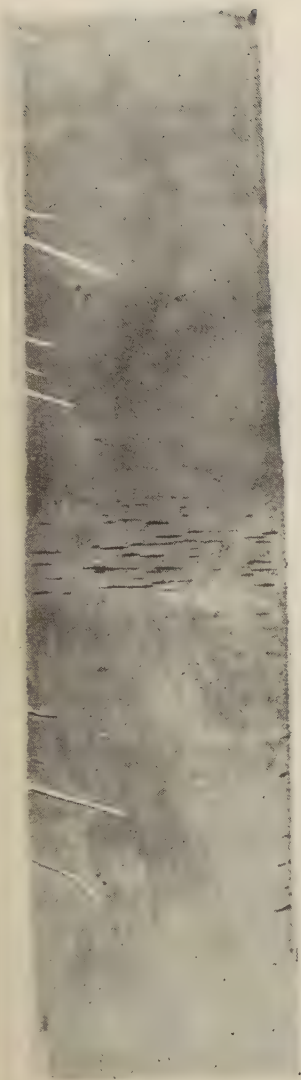


FIG. 10.—Special tensile test shackles and drilling jig.

The high-carbon steel strip oil-hardened from $850^{\circ}\text{C}.$, and tempered at $300^{\circ}\text{C}.$ or a lower temperature, or untempered, and then subjected to deformation while in this condition developed pickling cracks. None of the cold-rolled, and cold-rolled and tempered, samples were susceptible. Attempts to produce pickling cracks in the alloy steel strip in various conditions were unsuccessful.

OTHER METHODS OF PICKLING.

In the preceding experiments the standardised pickling in 10 per cent. sulphuric acid was employed. The effect of other methods of pickling was examined in order, if possible, to find means of pickling steel without embrittling it. The earlier experiments indicated that the embrittling effect of pickling is of general occurrence except in the softest steels. The subsequent experiments were, therefore, made on the steel which showed greatest susceptibility—that is, the medium-carbon steel strip.

Pickling medium-carbon steel strip in the oil-hardened from $850^{\circ}\text{C}.$, and tempered at $300^{\circ}\text{C}.$, condition for 30 min. in a bath consisting of 10 parts of concentrated hydrochloric acid and 90 parts of water by volume maintained at $50^{\circ}\text{C}.$ was found to have a pronounced embrittling effect, slightly less, however, than that of 10 per cent. sulphuric acid, as shown by bend tests.

Similar samples pickled in 10 per cent. nitric acid (by volume) at $50^{\circ}\text{C}.$ were severely attacked, and after 5 min. had suffered an appreciable reduction of section. There was only a very slight reduction of bending properties.

Experiments were made with 10 per cent. sulphuric acid containing colloids. When glue was added in an amount equal to 0.15 per cent., the attack of the steel by the acid was much retarded; there was hardly any noticeable evolution of hydrogen. As shown by bend tests, the embrittling effect on medium-carbon steel in the condition mentioned above was severe, but slightly less than that of the plain 10 per cent. sulphuric acid. The difference between the effects of the two baths was so small as to be negligible in relation to practical considerations. Starch additions gave similar results; the embrittling effect was not reduced appreciably.

Pyridine and quinoline additions gave the most promising results. A bath of 10 per cent. sulphuric acid to which 2 per cent. of pyridine had been added showed a much less severe embrittling effect when used at room temperature than the plain sulphuric acid bath. There was still an appreciable embrittling effect, however. When the bath was used at 50° C. the embrittling effect was much greater. Quinoline gave very similar results, reducing the embrittling effect of a cold 10 per cent. sulphuric acid bath substantially when added to the extent of 2 per cent. by volume. The quinoline baths were free from objectionable odour, but the pyridine baths were found to be unsuitable for practical use on account of the pyridine. The bend test results given in Table V. were obtained with cold-rolled medium-carbon steel strip.

TABLE V.—*Bend Tests on Cold-Rolled Medium-Carbon Steel Strip.*

Condition of Test-Piece.	Longitudinal.		Transverse.	
	Limiting Radius of Bend.	Reverse Bend.	Limiting Radius of Bend.	Reverse Bend.
Unpickled	0.5T	3.5	5T	0.5
Pickled in—				
10% H ₂ SO ₄ at 50° C. for 30 min.	8T	60° on P.B.*	15T	45° on P.B.
10% H ₂ SO ₄ + 0.2% pyridine .	7T	90° " "	13T	45° " "
10% H ₂ SO ₄ + 2.0% pyridine .	6T	0.5 "	11T	45° " "
10% H ₂ SO ₄ + 2.0% pyridine at 14° C. for 30 min.	4T	1.5	7T	60° " "
10% H ₂ SO ₄ + 2.0% quinoline at 14° C. for 30 min.	4T	1.0	6T	45° " "

P.B. = preliminary bend.

* Sample failed at 60° on the preliminary bend.

Pyridine and quinoline additions retarded the action of the acid on the steel to a great extent. There was very little evolution of hydrogen, and rust was removed less rapidly than in an ordinary pickling bath.

Tests were also made with sulphuric acid baths containing a proprietary organic preparation for addition to pickling baths. The embrittling effect was reduced appreciably, being approximately equal to that obtained with a bath containing 2 per cent. of pyridine. As with pyridine baths, the embrittling effect was greater when the bath was used at elevated temperatures.

Electrolytic Pickling.

Experiments were made on medium-carbon strip in the cold-rolled and in the oil-hardened from 850° C. and tempered at 300° C. conditions, in order to ascertain the embrittling effects of electrolytic pickling processes. The sample under observation was placed midway between two other samples of the same material and of the same size, connected in parallel and at a distance of 3 in. one from the other. Details of the experiments are given in Table VI.

Electrolytic pickling in 10 per cent. sulphuric acid (by volume) was accompanied by severe embrittlement, both in anodic and cathodic applications. Cathodic pickling appeared to be more effective for the removal of scale than standard pickling.

Anodic pickling in caustic soda solutions prepared from caustic soda of commercial quality (78 to 79 per cent.) gave no appreciable embrittling effect. Scale and rust were not removed effectively under the conditions employed. When pure caustic soda was used the results were the same as regards anodic pickling. Cathodic pickling in solutions of commercial caustic soda had an appreciable embrittling effect, but the latter was much smaller than that of sulphuric acid pickling. In solutions prepared from pure (A.R.) caustic soda the embrittling effect of cathodic pickling was scarcely discernible by bend tests.

Anodic pickling in 10 per cent. sodium chloride solution was not accompanied by any noticeable embrittling effect. The surface of the pickled samples was free from rust and scale, and their matte, metallic appearance was very pleasing. Precipitation of ferrous and ferric hydroxides which occurred during the pickling rendered the bath muddy. Cathodic cleaning in this solution did not have any embrittling effect, but the de-scaling properties were poor.

A solution containing 100 grm. of sodium carbonate, A.R., and 100 grm. sodium bicarbonate, A.R., per litre had only a very slight embrittling effect, whether used anodically or cathodically.

A bath containing 37.5 grm. of sodium cyanide and 25 grm. of commercial caustic soda per litre had a very slight embrittling effect when used anodically; when used cathodically the embrittling effect was very severe.

The experiments indicated that steel covered with a heavy

TABLE VI.—*Influence of Electrolytic Pickling under Various Conditions on the Bending Properties of Medium-Carbon Steel Strip.*

Electrolyte.	Temp. ° C.	Time.	Current Density, Amp. per sq. ft.	Polarity.	Condition of Steel.	Bend Tests.			
						Longitudinal.		Transverse.	
						Reverse.	Limiting Radius.	Reverse.	Limiting Radius.
10% H_2SO_4 , A.R.	50	30 min.	50	Cathode	O.-H. 850° C., T. 300° C.	45° on P.B.	80T	30° on P.B.	120T
	50	30 "	50	Anode	" 850° " " 300° "	45° " "	54T	45° " "	60T
	50	...	...	...	Do., unpickled	1-5	1-5	45° " "	7T
NaOH commercial, 25 grm. per litre	20	1 hr. 40 min.	4	Cathode	As received	0-75	5T	90° on P.B.	7T
	...	...	...	...	Do., unpickled	3-5	0-5T	0-5	4T
	20	1 hr. 40 min.	4	Cathode	As received	1-5	4T	90° on P.B.	7T
NaOH commercial, 100 grm. per litre	20	1 " 40 "	4	Anode	" "	3-5	0	0-5	5T
	50	1 " 40 "	4	Cathode	" "	1-5	3T	90° on P.B.	7T
	50	1 " 40 "	4	Anode	" "	3-5	0-5T	0-5	5T
	20	30 min.	50	Cathode	" "	2-5	2T	90° on P.B.	6T
	20	30 "	50	Anode	" "	3-5	0-5T	0-5	5T
	20	30 "	50	Cathode	" "	2-5	2T	90° on P.B.	6T
	50	30 "	50	Anode	" "	3-5	0-5T	0-5	5T
	...	...	...	...	Do., unpickled	3-5	0-5T	0-5	4T
	50	30 min.	50	Cathode	O.-H. 850° C., T. 300° C.	1-5	3-5T	45° on P.B.	8T
	50	30 "	50	Anode	" 850° " " 300° "	1-5	3-5T	45° " "	8T
	...	...	...	...	Do., unpickled	1-5	3-5T	45° " "	7T
	50	30 min.	50	Cathode	O.-H. 850° C., T. 300° C.	1-5	4T	45° on P.B.	10T
10% NaCl	50	30 "	50	Anode	" 850° " " 300° "	1-5	4T	45° " "	8T
	50	30 "	50	...	Do., unpickled	1-5	3-5T	45° " "	7T
	...	...	...	...	O.-H. 850° C., T. 300° C.	1-5	4T	30° on P.B.	8T
100 grm. NaOH, A.R., 100 grm. $NaHCO_3$, A.R., per litre	20	2 hr. 30 min.	10	Cathode	" 850° " " 300° "	1-5	4T	30° " "	8T
	20	30 min.	50	Anode	" 850° " " 300° "	1-5	4T	30° " "	8T
	20	30 "	50	...	Do., unpickled	1-5	3-5T	45° " "	7T
37-5 grm. NaCN, 25 grm. NaOH, commercial, per litre	...	...	...	...	As received	90° on P.B.	6T	90° on P.B.	9T
	20	1 hr. 40 min.	4	Cathode	" "	3-5	1T	0-5	0-5T
	20	1 " 40 "	4	Anode	Do., unpickled	3-5	0-5T	0-5	4T

O.-H. = oil-hardened ; T. = tempered ; P.B. = preliminary bend.

scale could be cleaned more effectively by electrolytic pickling in 5 to 10 per cent. sulphuric acid as cathode, or as cathode and anode alternately, than by electrolytic pickling in alkaline solutions. For removing grit, grease, residues of carbides, and non-metallic matter, the alkaline electrolytic pickling or cleaning baths described gave satisfactory results without serious embrittlement, with the exception of cathode treatment in cyanide baths. It was found that the brittleness induced by electrolytic pickling could be removed almost completely by heating, in the same way as that due to ordinary pickling.

It is of interest to note that Edwards ⁽⁷⁾ stated that the diffusion of hydrogen could be prevented by electrolytic pickling.

ANALOGY OF PALLADIUM.

The absorption of hydrogen by iron appears to be analogous to the more fully investigated absorption by palladium. Andrew ⁽⁹⁾ stated that the rate of absorption of hydrogen by palladium is increased by cold-working, and is greatest for palladium in a finely divided form. It is known that hydrogenised palladium gives off its hydrogen on standing in air, and the liberation of hydrogen is more rapid at elevated temperatures. Yamada ⁽¹⁰⁾ investigated the X-ray spectrogram of hydrogenised palladium, and found it was not altered by hydrogen except for a slight contraction of the intervals between the lines. This indicated uniform expansion of the space lattice by hydrogen, and is evidence of the solution of hydrogen in the metal as opposed to the formation of a palladium-hydrogen compound.

McKeehan ⁽¹¹⁾ investigated the spectrograms of palladium and of hydrogenised palladium. He suggested two crystallographic arrangements by which hydrogen could be absorbed without a modification of the cubic symmetry. The suggested arrangements were purely speculative, and McKeehan considered that there was no X-ray evidence of the position of the hydrogen atoms. The change in resistance was linear throughout the greater part of the range of occlusion, a criterion of the existence of two phases. Partially saturated palladium gave a diffraction pattern in which each line was doubled, there being a clear space between each pair of lines. This was interpreted as signifying the

existence of two phases, one being practically pure palladium and the other a saturated solution of hydrogen in palladium.

Hydrogenised palladium gives off its hydrogen on standing in air, and the liberation of hydrogen is more rapid at elevated temperatures. From X-ray spectrograms of platinum-black and palladium-black, Osawa⁽¹²⁾ concluded that gases are held in solid solution by these substances. He observed an expansion of 2 to 3 per cent. of the linear dimensions of the lattices. Koch⁽¹³⁾ found that the electrical resistance of palladium was increased by hydrogen, and an increase in that of iron due to the presence of hydrogen was observed by Johnson.⁽¹⁾

CONCLUSIONS.

1. In general, steel is embrittled by pickling in the usual manner in sulphuric acid and other acid solutions. The degree of brittleness is dependent on the composition and condition of the steel, as well as upon the conditions of pickling.

2. The brittleness produced by pickling a particular steel is, in general, greatest when the steel is in its hardest condition, and least when the steel is in its softest condition.

3. Immersion in boiling water for 30 min. substantially removes the brittleness due to pickling, giving practically the maximum recovery. The same result is achieved by allowing the pickled steel to stand for several days at normal temperatures.

4. The embrittling of steel by pickling may be accompanied by a reduction in tensile strength. Such a reduction has been observed only in steels which are capable of being rendered relatively hard by heat treatment, and in these steels only after hardening and tempering, if at all, at low or moderate temperatures.

5. If medium- and high-carbon steels, hardened, and tempered in a certain range of temperature, be subjected to deformation while in that condition, they are liable to develop cracks during pickling at the places where deformation had occurred. It has been shown that these cracks are produced during the pickling operation, and complete fracture may ensue. Pickling cracks have not been observed in the mild steel nor in the alloy steel investigated.

6. The addition of certain organic substances to a pickling bath affects the attack of the acid upon the steel. So far, it has been found that the addition of organic substances and colloids to the pickling bath does not prevent the embrittlement of the steel, but certain compounds diminish it considerably, notably pyridine and quinoline.

7. Pickling electrolytically in neutral or alkaline solutions can under certain conditions be effected without appreciable embrittlement of the steel. In this respect anodic pickling was generally found to be less injurious than cathodic.

8. The experiments have confirmed the work of other investigators, and they afford additional evidence of the deleterious effect of hydrogen generated at the surface of steels during pickling operations.

In conclusion, the author gratefully acknowledges the assistance and advice of Mr. W. H. Dyson of the Air Ministry; of Mr. W. D. Douglas, Mr. I. J. Gerard, and Miss Pettifor of the Mechanical Test Department of the Royal Aircraft Establishment, who designed the special jig and shackles, and made the tensile tests; of Mr. C. W. George, Mr. A. J. Sidery, and other colleagues of the Metallurgical Department. The author is indebted to the Air Ministry for permission to publish this paper. It will be understood that this paper is a personal contribution, and that responsibility for statements made and opinions expressed rests solely upon the author, and not upon the Air Ministry.

APPENDIX.

Reverse Bend Test.

The sample is fixed in a vice, the jaws of which are rounded to a radius equal to three times the thickness of the steel sheet to be tested. The projecting portion is then bent at right angles to the fixed part, and then backwards and forwards through an angle of 180° until it fails. The preliminary bend to 90° is not counted. The width of the samples tested was $\frac{1}{2}$ in.

Limiting Radius Bend.

The samples are bent to 180° round rods of diminishing diameter. The smallest radius about which the strip may be bent to 180° without showing signs of failure is taken as the limiting radius of bending, and this radius is expressed as a multiple or a fraction of the thickness of the strip.

Tensile Test.

Preliminary tests on the pickled samples of the harder materials were unsatisfactory. Fracture occurred at the head more frequently than on the parallel portion of the test-piece.

The special shackles were designed for tensile tests on thin sheets, using ball alignment as in the "Robertson shackles" *; they are illustrated in Fig. 10 (Plate XXIII.). In the foreground may be seen the special drilling jig, so constructed as to ensure accurate alignment of the test-pieces relative to the axis of pull. Tests made with these shackles gave consistent results. In order to avoid fracture in the heads of the harder test-pieces, each end was tempered slightly in a Bunsen flame, the rest of the test-piece being meanwhile immersed in cold water.

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* See C. F. Jenkin, "Materials of Aircraft Construction."

DISCUSSION.

Dr. W. ROSENHAIN, F.R.S. (National Physical Laboratory), asked the author whether he had tried to arrive at any idea as to why cracks, under certain conditions which he had described, really occurred, and as to the nature of the mechanism by which the brittleness was produced. That had not been the object of the paper, but he should imagine that an investigator dealing with a problem of such a kind would form some opinion on the reasons why those things happened. It occurred to him that since fully hardened high-carbon steel, when pickled, tended to crack, and that even after tempering, if it were then cold-worked, it also tended to crack, it might therefore be a question of internal stresses developed by the absorption of hydrogen during pickling; and he would like to ask two questions: Did the recovery mean the substantial removal of hydrogen from the steel or did it merely mean a change of the condition in which that hydrogen was present in the steel? In other words, if that steel were tested immediately after pickling while still in the brittle condition, would a larger amount of hydrogen be found in it, if it could be extracted, than there would be after standing? He imagined that there would, but it would be interesting to know whether that had ever been actually proved. The second question was: Were internal stresses developed in the steel by the absorption of hydrogen during pickling? That problem could be attacked in some such way as the following. Supposing one prepared a ring of fairly high carbon steel, and hardened it, and then ground a slit in it so as to relieve most of the stresses. No doubt when the slit had been ground, the ring would tend either to open or close, according to the nature of the hardening stresses remaining in it. The amount of such opening or closing should then be measured as accurately as possible, and subsequent measurement would show whether, after pickling, the slit ring opened or closed more than before, and also whether during the subsequent recovery that change of dimension was reversed. One would then have not only a means of knowing whether actual internal strain (he used the word in its strict sense) was produced, but also whether that strain was removed, or whether the stress was merely released by some internal rearrangement.

Such matters might at first sight appear to be of an academic or theoretical nature, but they were really very important, because it was not until it was known exactly what happened in such cases that more general ideas on the subject could begin to be formed, and the possibilities of that kind of action be appreciated. What he had in mind was that a large amount of work had been done in recent years on the simultaneous effect of corrosion and fatigue; that did not at first sight appear to be related to pickling, but it was quite possible

that the kind of action which led to embrittlement, and occasionally to the disruption of articles during pickling, might have something in common with the action which occurred when corrosion and fatigue co-operated in bringing about the failure of a piece of steel.

Mr. T. H. TURNER (Birmingham) said, in view of Mr. Sutton's reference to the lack of information on the subject, it might be useful to make public the fact that in the Birmingham University Library there was the manuscript of an M.Sc. thesis, written in 1926 by Mr. I. G. Slater, covering much of the ground. Mr. Slater had first tested wires; afterwards he had tested a whole range of carbon steels. The most interesting and unexpected result had been that under the notched-bar impact test, his steels, instead of becoming more brittle, had become apparently tougher. One might explain that, perhaps, by the notch having been eaten out a little, or by some cold-worked material at the bottom of the notch having been removed. In tensile tests Mr. Slater had found an increase in strength which varied according to the carbon content. He had also carried out recovery tests, and his results agreed entirely with those of the author. Two other tests of Mr. Slater's were worth mentioning—the ordinary static Brinell and the impact Brinell. Strangely enough his results had given an increase up to about 10 per cent. in the static Brinell hardness, and a decrease in the impact hardness.

So far as the paper was concerned, it seemed to him to show that if one could not be satisfied with the strength of mild steel, and it was necessary to pickle the article, one must turn, not to medium-carbon steel, but to the nickel-chrome alloy steel mentioned, or to some other alloy steel, in order to avoid the pickling trouble.

Professor T. TURNER (Member of Council) said the subject of embrittlement of steel by hydrogen was one which had for long interested metallurgists; he remembered hearing their late President, Dr. Percy, refer to that property a good many years ago. Several experiments on the subject had been conducted at Birmingham, and some of the results were most surprising. He had expected that since the steel became brittle it would become weaker when it was pickled, or when it was used as a pole for a battery. Instead of that it was found in some cases that the tensile strength of the steel actually increased; but after allowing the material to remain in boiling water it reverted to its original condition. One of the most striking small experiments he had seen made on that subject consisted in carefully and suitably pickling a piece of steel of the character of a watch-spring; it could then be broken in one's fingers. If it were boiled in water it entirely recovered its original properties, and it was impossible to perceive from any test that it had been brittle in the interval.

He sympathised with Dr. Rosenhain's wish to know what was the explanation. So far as the evidence submitted in the paper was

concerned, the hydrogen apparently went into solid solution; it did not go in between the crystals or have anything to do with the crystal boundaries, yet it might produce a marked effect, and it disappeared in a mysterious manner. He assumed that, as a return to the original properties took place, the cause of the trouble had completely gone, but that might be a mistaken assumption, and some might still remain.

Mr. J. H. WHITELEY (Consett) said that both Dr. Rosenhain and Professor Turner had asked the same question that he had in mind. Where did the hydrogen absorbed in pickling get to? Was it retained by the steel, or liberated? He would suggest that the method described by Mr. Rooney in his paper on the estimation of hydrogen¹ was admirably suited for the study of that problem. There was a point, also, which he (Mr. Whiteley) had mentioned at a previous meeting, and which he thought might here be considered—namely, that the mere passage of atomic hydrogen in large volume through the metal might of itself, in certain cases depending upon grain boundary conditions, set up brittleness. He was particularly interested in the subject as it concerned the galvanising process. There appeared to be at least three forms of brittleness which could be produced in dead soft steel during its manufacture into galvanised sheets. One was due to pickling, and it was of interest to have it confirmed by Mr. Sutton that its removal was easy. Another was that dealt with in Mr. Bolsover's paper.² There, also, heating the steel to about 100° C. seemed sufficient to eliminate it. He (Mr. Whiteley) had several times found a third form, however, which was not removed until the steel had been heated to above 500° C. Galvanised sheets showing that type of brittleness could be readily smashed with a hammer, and he had not found that extreme brittleness to disappear at any lower temperature. It occurred chiefly in the thicker class of material, and there were probably two or more contributory causes. He thought that pickling might be one of them.

Professor T. TURNER (Member of Council) hoped that members of the general public would not imagine that the brittleness referred to was a cause of danger in steel. The cause of the brittleness referred to was not a thing that entered into manufacture; it was merely temporary, and would pass away.

Mr. J. MITCHELL (Coatbridge) said there were two points in particular to which he desired to refer. The first was that recently he had been working on similar lines to the author, and, generally, he had confirmed his results. He found, for instance, that practically all the mild steel of commerce was subject to the embrittling phenomenon referred to. It was found also that a very short treatment in boiling water was sufficient to remove it, and from the steel user's point of

¹ This volume, p. 573.

² This volume, p. 473.

view the very reassuring fact was established that, even if the steel were not subjected to hot-water treatment, the phenomenon disappeared after a few days. The author had stated that the sample of mild steel used was a typical mild steel. He ventured to say that the author would not find 10 per cent. of the mild steel of commerce with something over 0.10 per cent. of silicon. That was rather an important point, because he (Mr. Mitchell) found in his work that the percentage of silicon had a very considerable effect on the occurrence or non-occurrence of that particular phenomenon. He also desired to suggest that, from a pickling point of view, especially in view of the recovery in hot water, the temperature of the pickling solution might have something to do with the sensitiveness of the material to the phenomenon.

Dr. F. JOHNSON (Birmingham) said that in the early days of the late war he had had some experience of the embrittlement of mild steel when electroplated with various metals, and he ventured to suggest there was a possibility that such embrittlement would not be quite so evanescent as the embrittlement due to pickling. He did not know whether embrittlement (due, no doubt, to the occlusion of hydrogen) in the electroplating operation had been studied by the author, but it was a subject worth taking up.

The PRESIDENT desired to ask a question. Odd cases had occurred now and again in which wire ropes, especially colliery wire ropes, had broken suddenly without any apparent reason. It was well known that mine waters were occasionally acid, and he would like to know whether, in the author's opinion, it was possible for such a very dilute acid as a mine water—that was, dilute as compared with the acid with which the author had worked—could have produced a similar embrittling effect. The wires were always of a medium high-carbon type, and had always had a fair amount of work upon them, so that apparently they were in a sensitive condition for receiving the embrittlement, if it were possible for such a solution to cause it.

Mr. SUTTON, in reply, thanked the various members who had contributed to the discussion. Dr. Rosenhain had inquired whether he had considered the question why the cracking phenomenon to which reference was made occurred. He had given much consideration to the matter and had found it was beset with many difficulties. The whole question seemed to demand a more complete understanding of the formation of adsorption compounds by metals, the change-over from adsorption compounds to chemical compounds, and the question of the true solution of gases by metals. He had been following very closely the question of the adsorption of hydrogen by platinum-black and, in particular, by palladium, but the question had not yet been definitely settled. His reading of about five papers on investigations with the

X-ray spectrograms of palladium had led him to the conclusion that three people thought that a compound was formed and two did not. The investigations of Yamada and Osawa mentioned in the paper led to the conclusion that hydrogenised palladium held the hydrogen in solid solution. That of McKeehan, also mentioned in the paper, and the more recent investigations of Linde and Borelius¹ and of Hanawalt² indicated that a compound Pd_2H was formed.

He did not know at present of any similar investigation in the case of iron and hydrides of iron, but it was a question which merited attention. Some years ago an American investigator, Morrison,³ had claimed to have observed under the microscope the effect of pickling on the microstructure of steel. For a long time he failed to see either in the reproductions of Morrison's micrographs or in his own microscopic work any evidence of that effect, but he was inclined to think that in recent experiments with certain steels on which the effect of pickling was large there was a change in the microstructure.

He thought no one could dispute the fact that stresses were developed by pickling, but in many cases measurement was obscured or made very difficult by the fact that the harder steels were generally in a state of strain, and there were very peculiar internal stresses in most parts that had a high degree of hardness. He quite agreed that the question of corrosion fatigue was very closely related in character to that of the influence of pickling. Mr. Turner had mentioned Mr. Slater's thesis on the influence of pickling on steel and what was to him a most interesting point—namely, that the Izod value of steel was liable to be increased by pickling in acid. He thought that Mr. Turner's suggested explanation was a plausible one. Personally, he had no appreciable experience on that particular point. Professor Turner had mentioned the behaviour of a watch-spring, which could very easily be broken in the fingers after pickling. He quite agreed that the possibility of a solid solution formation appeared to be very great, but it was a little difficult to reconcile just a simple solid solution theory with the various facts that had been observed, such, for instance, as the formation of pickling cracks, the loss of brittleness on standing in air, and so on. Mr. Whiteley had asked where the hydrogen went to. It seemed inconceivable that the embrittling effect of pickling could be due to a surface effect only. He had ground off quickly, under ideal conditions with severe cooling, the surface from different specimens, and had found them to be still brittle, so that down to a depth of 0.003 or 0.004 in. the brittle conditions still persisted. He quite agreed that there was scope for the application of Mr. Rooney's method of determining hydrogen to the question of hydrogen penetration in steel.

Dr. Johnson had touched on an important matter when he said that possibly the embrittlement due to electroplating was not so

¹ Linde and Borelius, *Annalen der Physik*, 1927, vol. lxxxiv. p. 727.

² Hanawalt, *Physical Review*, 1929, vol. xxxiii. March, p. 444.

³ C. J. Morrison, *Iron Age*, 1921, vol. cviii., Aug. 11, p. 334.

evanescent as that due to pickling. He had had a little experience which indicated that that was distinctly the case, and that, with certain metals which were commonly electro-deposited, it was not by any means so easy to get rid of the brittleness of the plated steel as that of pickled steel. On the other hand, with thin electro-deposits of cadmium and zinc (0.0003 to 0.0005 in.) on steel, it was possible to get rid of the brittleness substantially.

Dr. JOHNSON asked whether Mr. Sutton referred to standing or heating.

Mr. SUTTON said he referred to heating only; temperatures in the range of 100° to 150° C. had given satisfactory results. On standing some recovery did take place, but it was somewhat slow; it was a matter of some weeks, at any rate, before reasonable ductility was regained.

The President touched on a very interesting point in connection with the possible cause of fracture of colliery ropes. That was a subject of which he (Mr. Sutton) had no personal experience, but he suggested that if the ropes were in prolonged contact with an acid mine water there was very little doubt that the mechanical properties would be substantially affected. The researches of McAdam on the corrosion fatigue of steel, to which Dr. Rosenhain had referred, had shown that the fatigue properties of steel were reduced very seriously by contact with natural waters. He would reply to other points in writing.

This paper was also discussed at the Additional Meeting held at Sheffield on May 15, 1929.

Dr. L. B. PFEIL (Swansea) said that in South Wales, where pickling was an extremely important stage in the manufacture of tinplate and galvanised sheet, Mr. Sutton's paper had been received with great interest. Mr. Sutton had made clear the influence of previous deformation on the development of brittleness by pickling. It seemed to him (Dr. Pfeil) that the reasons for the development of pickling brittleness in cold-worked steel and in quenched steel might be very similar; in both cases it might be due to the presence of internal stresses before the pickling operation. Internal stress was certainly present in both cold-worked and in quenched steels. On pickling such steels the entrance of atomic hydrogen might expand the lattice, and that was equivalent to additional tensile stress. If the stress already present before the pickling were sufficiently great, then the added stress due to the entrance of hydrogen might overcome the strength of the steel and cause total or partial fracture during the pickling operation; or, if the original stresses present were less intense, failure might not occur until still further stresses were applied in the bend test.

Mr. Sutton had referred to some work which he (Dr. Pfeil) had carried out on "The Effect of Occluded Hydrogen on the Tensile Strength of Iron."¹ In the course of that research he had found that pickling brittleness was removed by cold-working. It seemed to him that it was important to bear that fact in mind when carrying out mechanical tests; in bend testing, the rate at which the first few bends were made might have an important effect on the total number of bends required for failure, for gentle cold-working during the first bend might cause the rapid evolution of the whole of the hydrogen and the disappearance of the embrittling effect before the completion of the test. He hoped that Mr. Sutton would carry out an experiment on those lines, using specimens which he knew would show brittleness if tested in the ordinary way.

Dr. W. H. HATFIELD (Member of Council) remarked that the wide cracks in Fig. 9 did not look like stress cracks; they appeared rather as though metal had been bodily removed, and that would point to a differential solubility, due to a difference in the surface or to some other cause.

Mr. SUTTON, in reply, said he was pleased to have Dr. Pfeil's interesting remarks, in view of his past experience of the effects of hydrogen on iron. It was scarcely possible to discern the embrittling effect of pickling in 10 per cent. sulphuric acid on medium-carbon steel which had been close-annealed and cooled at a very slow rate. On normalised steel there was quite a discernible embrittling effect compared with that on the dead soft close-annealed material. Dr. Pfeil's remarks on the influence of internal stresses resulting from the heat treatment or cold-working operations were probably very near the truth. It was, of course, a common experience that fully hardened carbon steels were liable to crack during pickling. As regards the suggestion that the notching effect of the pickling might be very serious, he had given some consideration to that point also, but it was a little difficult to conceive of the small cracks produced by pickling actually healing, and enabling one to get the high degree of recovery which was possible. He appreciated the suggestion of a slow preliminary bend; he had not tried making bend tests in that way, but would do so.

In reply to Dr. Hatfield's comments on the cracks visible in Fig. 9, Mr. Sutton pointed out that they were not in the original form. As reproduced, they were enlarged by two approximately. The wider cracks formed early in the pickling, and widened during further pickling. Slight further widening had occurred when the sample was cleaned in nitric acid for photographing.

¹ *Proceedings of the Royal Society*, 1926, (A), vol. cxii. p. 182.

CORRESPONDENCE.

Mr. H. BREARLEY (Sheffield) wrote: The paper appears to be a very neat parcel containing most of what is already generally known about the embrittling effects of pickling, but it does not add much that is new. After saturating himself with the literature of the subject the author should be in a good position to carry his investigations a stage further. Could he tell us, for example, whether the brittleness of the pickled sample is confined to the outer portions of the steel, or whether the pickled sample is equally brittle in its interior?

The paper gives one the impression that the author is able to develop brittleness in steel in a measured degree. If he has that command over the operation, then he should be able to make some useful observations on the behaviour of hardened steel tools. A piece of intensively water-hardened tool steel of fairly intricate shape which may have remained sound for many years is very apt to crack when pickled, and the cracks developed mark out paths which one imagines are those where the hardening stresses are greatest. When any large number of similar tools are water-quenched, a few may break and the bulk of them remain sound, but no one can tell by a visual examination of the tools which of the apparently sound tools are on the point of breaking. If the brittleness of the steel could be increased by a measured amount by some pickling operation it should be found, one thinks, that a number of sound tools, after such pickling, would crack; and if the brittleness could be further increased (by some other form of pickling) more of the sound tools would break when pickled. In this way the author might arrive at some very interesting information relating to the degree and distribution of stresses in hardened steel tools. A few preliminary experiments along these lines have already shown that the hardness of the steel tool and its tendency to crack on pickling are not closely related. There appears to be a much closer relationship between the tendency to crack and the manner in which the steel tool is heated for hardening or the medium in which it is quenched.

On p. 200 the author states that the brittleness produced by pickling a particular steel is greatest when the steel is in its hardest condition. Obviously the effects of pickling steel in the hardened condition are more dangerous than when the same steel is pickled in the soft condition, but it would be interesting to know how the author has convinced himself that the actual amount of brittleness due to pickling is greatest when the steel is in its hardest condition.

Mr. A. M. PORTEVIN (Paris) wrote: The fissuration of samples of carbon steels by corrosion after bending should, no doubt, be related

to the phenomenon of corrosion under tensile stress known as "corrosion cracking"; deformation by bending is a non-uniform deformation, which causes unequal cold-work and, consequently, internal stresses. Annealing after bending relieves the stresses, and fissuration then stops.

In the case of brass, the internal stresses may be demonstrated by the mercurial etch, which develops fissures; it may be used for purposes of both demonstration and study.¹ In steel, the observation of fissuration in non-uniformly cold-worked materials is more rare; this phenomenon has been observed after pickling shells which had been deformed permanently to allow driving bands to be fitted on them²; Jones' experiments on the action of salt solutions on deformed steels may also be quoted.³

Whereas, in the case of brass, the determining conditions and the necessary values of the various factors for corrosion cracking to occur are so well understood that the phenomenon can be brought about with certainty and at will, in the case of steel, the various essential factors (minimum stresses for fissuration, nature and optimum composition of the corroding liquids) are far from being known, and the occurrence of the phenomenon under the conditions which have been recorded can only be regarded as "probable."

The author's observations are interesting from that point of view, and it will be useful to know the degree of bending and the composition of the corroding reagent which enable fissuration to be brought about with certainty.

Mr. I. G. SLATER (Malvern) wrote: The author has shown that pickling effects are more marked in the steels more amenable to heat treatment; in this direction the writer has made experiments in which it was attempted to determine the relationship between the carbon content and the changes produced by chemical and electrochemical pickling. It is generally held that the effects of pickling are of a deleterious nature. The writer's experiments show, however, that this is not necessarily the case, but is dependent on the method of testing adopted. Two forms of material were tested—namely, rolled bars having various carbon contents, and drawn wire of the higher carbon type. The wire samples were representative of the various high-tensile types produced by the cold-drawing of patented or sorbitised wire, and were tested in both the drawn and the patented condition. The usual wire torsion test was employed to determine the extent of the changes produced on pickling. Chemical pickling in mineral acids, including nitric acid (in which nascent hydrogen is an initial product of the reaction), was found to reduce the torsional value (number of twists on an 8-in. test length before fracture) in every instance, the reduction

¹ A. M. Portevin, *Revue de Métallurgie, Mémoires*, 1929, vol. xxvi. p. 72.

² A. M. Portevin, *Journal of the Iron and Steel Institute*, 1923, No. II. p. 71.

³ J. A. Jones, *Transactions of the Faraday Society*, 1921, vol. xvii. p. 102.

being a function of time, temperature, and concentration, or, in general, a factor of the rate of chemical reaction. Hard-drawn wire appeared to suffer a greater deterioration than the patented samples. The rapidity with which embrittlement ensued after immersion in the acid was a notable point; immersion for 5 min. in 20 per cent. sulphuric acid at 20° C. was sufficient to reduce the torsional value nearly to the minimum obtainable after more prolonged pickling. The recovery of embrittled wire was dependent upon its after-treatment. Heating to 100° C. for 2 to 3 hr. in an air-oven, or for 1 hr. in boiling water, sufficed to restore fully embrittled wire. At room temperature several days' exposure was required before recovery approached completion. It was found that there was some indication of a permanent deterioration after recovery, especially in the hard-drawn samples, illustrated not only by failure to reach the original torsional value, but also by the fact that certain of the "recovered" specimens fractured in more than one place simultaneously on testing—a criterion generally held to be indicative of defective material. The results of tests in which various substances, such as flour, starch, yeast, &c., were added to the pickle were similar to those recorded in the paper. Stannous chloride was found to be an excellent inhibitor in this respect, a deposit of tin being formed on the surface of the freshly exposed metal under the scale (with patented samples), immediately reducing acid attack and consequent embrittlement to a minimum. It was also found that by immersing embrittled specimens in certain oxidising solutions, such as permanganate or even nitric acid, recovery could be expedited. With nitric acid almost complete recovery was rapidly attained, followed by subsequent embrittlement.

Steels of heavier section having various carbon contents were next examined. They were of acid open-hearth manufacture, and were tested in the normalised condition. By far the most interesting results were obtained in the impact tests made on the series. A special test-piece was employed—rendered necessary by the original size of the material and the capacity of the Izod machine available—having a diameter of 10 mm. and notched circumferentially, 1 mm. deep, with a tool having an angle of 66° with a tip radius of 0.25 mm. Chemical pickling on certain of the steels showed that, whereas a reduction in impact resistance had been logically anticipated from previous results, actually the impact value had very considerably increased. It was thought that this might be due to the erosion of the notch by the acid, but on sectioning similar notches in the same test-pieces which had given the higher values, it was found that the contour of the notch had not materially changed. In order to eliminate this possible influence, electrochemical pickling as cathode, in which process chemical solution of the metal does not occur, was resorted to. The results of impact tests made on the series before and after electrochemical pickling as cathode in 20 per cent. sulphuric acid, with a current density of 0.5 amp. per sq. cm., are given in the following table:

Carbon Content, %	Notched-Bar Impact Value. Ft.-lb.			
	Not Pickled.	Pickled—		
		For $\frac{1}{2}$ Hr.	For 3 Hr.	For 17 Hr.
0.21	20.0	26.0	25.0	25.3
0.315	14.8	20.5	17.0	13.9
0.415	10.8	8.7	10.9	11.4
0.50	5.3	4.7	3.9	3.9
0.61	6.0	4.3	3.8	3.4
0.71	2.9	4.7	2.1	3.3
0.805	2.5	4.1	3.0	3.3
0.89	2.4	2.4	2.2	2.4
1.005	2.3	3.3	2.7	1.8
1.105	1.6	1.6	1.4	1.6

It will be observed that with certain of the steels very definite increases in impact value occurred; with a few, and generally after the 17-hr. treatment, decreases were obtained. There appears to be no definite relationship between the carbon content of the steel and the change in impact value obtained.

The fundamental difference between this test, which is a dynamic one, and the previous tests employed by other investigators, must necessarily modify our conception of the nature of the iron-hydrogen complex produced by pickling. From the work of previous investigators there is little doubt that hydrogen, or the effects of hydrogen, are common to the mass of the metal and are not superficial. It may be assumed that the hydrogen absorbed on pickling may exist in two phases, the one as a solid solution or equivalent phase of iron and hydrogen, and the second as dissociated or actual H_2 molecules concentrated at non-metallic inclusions, grain boundaries, &c. The writer advances the following tentative theory as to the nature of the iron-hydrogen complex formed on pickling, and its properties on testing.

On pickling, the iron absorbs hydrogen to form a solid solution phase or its equivalent. This phase is necessarily very unstable, and is decomposed on straining the metal as would occur in the ordinary tensile, bend, or torsion tests, resulting in the formation of the second phase. Actually, therefore, in such tests the original solid solution phase is not tested, but the second, which may be expected to show the characteristics of embrittlement. By testing the pickled metal dynamically as in the impact test, the properties of the first phase are determined, and it may be found to have superior properties in certain respects to the unpickled metal. Many methods present themselves for the further investigation of these points, such as dynamic tests of other types, and tests whereby purely physical characteristics are determined, including X-ray analysis, electrical properties, &c.

In a written reply, Mr. SUTTON stated: In further reply to Dr. Rosenhain's remarks as to whether recovery occurred by removal of hydrogen or by a change of condition of the hydrogen, no crucial evidence on that point had been obtained in the experiments. It appeared possible that both processes might occur.

He had made no attempts so far to measure stresses set up by pickling, but it might be of interest to mention that Koch¹ had recorded length increases of 1.5 to 8 per cent. for palladium treated with hydrogen.

Mr. Turner had mentioned the increase in Brinell hardness observed by Mr. Slater. In the author's tensile tests on the low to medium tensile carbon steel samples, a slight increase in tensile strength due to pickling was generally observed. The amount of the increase was usually small, however.

Referring to Mr. Mitchell's remarks, the mild steel described in the paper was not typical of the mild steel of commerce. From experiments on the effect of variation of pickling-bath temperature it appeared that the embrittling effect of a particular sulphuric acid bath tended to increase with increasing temperature, but the increase in the range 50° to 100° C. was slight.

In reply to Mr. Brearley, the embrittling effect of the standard pickling mentioned in the paper on steel wires certainly penetrated more than 0.005 in. from the surface.

As regards the behaviour of hardened steel tools, probably it would be best to avoid pickling altogether, and to carry out the necessary cleaning by sand-blasting or other means. Hardened tools would be already somewhat brittle before pickling, and the measurement of increased brittleness due to pickling would be a difficult matter. The tendency of hardened tools to crack on pickling would probably be influenced greatly by factors such as soundness of the steel, uniformity of composition, mass and form of the tool, &c. On p. 200 it was stated that "the brittleness produced by pickling is, in general, greatest when the steel is in its hardest condition." It was realised that some of the data given in the paper indicated slight deviations from that generalisation, but decreasing the hardness and tensile strength of the steels by the use of increasing temperatures of tempering generally caused convergence of the curves representing bending properties of the pickled and unpickled samples, and gave an indication that for fully softened material the embrittling effect would be very slight indeed. No such conclusion was reached regarding the pickling-cracking tendency.

In reply to Mr. Portevin, it appeared that a much higher degree of internal stress was required in steel than in brass in order to render it liable to crack on contact with appropriate reagents. Fortunately, steels were not generally used in conditions in which the susceptibility was great, but springs and other parts of hardened steel, tempered at low temperatures, were frequently left in such a condition. Owing to

¹ Koch, *Annalen der Physik*, Feb. 8, 1918.

the large number of steels, heat treatments, corroding and pickling media, &c., concerned in steel technology a large amount of experimental work was required.

Referring to Mr. Slater, the results given in his interesting communication bore very closely on his (Mr. Sutton's) experiments. The permanent deterioration of hard-drawn wires in Mr. Slater's tests might be due to the formation of pickling cracks, which would not be influenced by standing or by heating to 100° C.

With regard to impact tests, Brenier¹ observed that the pickling of a steel had no appreciable effect on the Izod value. He (Mr. Sutton) felt that the steels used in Mr. Slater's interesting series of Izod tests on steels of varying carbon content were probably rather too soft in the normalised condition to permit a general conclusion to be reached. Mr. Slater's theory appeared inconsistent with Pfeil's work, in which cold-working removed pickling brittleness.

¹ *Revue de Métallurgie, Mémoires*, 1925, vol. xxii. p. 568.

THE MECHANICAL AND METALLURGICAL PROPERTIES OF SPRING STEELS AS REVEALED BY LABORATORY TESTS.¹

By G. A. HANKINS, D.Sc., A.R.C.S., AND MISS G. W. FORD, B.Sc.

INTRODUCTION.

THE investigation described in the present paper has been carried out at the National Physical Laboratory as part of the systematic investigation of the mechanical and metallurgical properties of spring steels which forms part of the programme of the Springs Research Committee of the Department of Scientific and Industrial Research. The results of various other researches authorised by the Committee have been published by the Department, but the major part of the present paper forms a continuation of an investigation published by the Iron and Steel Institute in 1926.² The previous paper gave details of the results obtained in a laboratory investigation of a 0·6 per cent. carbon steel, a 0·8 per cent. carbon steel (both oil-quenched), a silico-manganese steel, and a chrome-vanadium steel. The present paper gives the results of similar tests on a low-chromium steel, a high-chromium steel, a nickel-chrome steel, and two water-quenched carbon steels, one of which is the 0·6 per cent. carbon steel mentioned above, and completes the investigation of steels falling within the limits of analysis specified by the British Engineering Standards Association for standard spring steels. In the course of the work, endurance fatigue limits have been determined on each steel in three or four conditions of heat treatment, but it is necessary to state that other experiments authorised by the Springs Research Committee have shown that, in regard to fatigue, the properties

¹ Communication from the National Physical Laboratory, received February 9, 1929. Research carried out for the Engineering Co-ordinating Research Board of the Department of Scientific and Industrial Research.

² Hankins, Hanson, and Ford, *Journal of the Iron and Steel Institute*, 1926, No. II. p. 265.

developed in actual laminated springs are far below those which would be anticipated from the results of the present tests. It should be clearly understood that the results of laboratory fatigue tests on prepared polished specimens give little or no indication of the actual fatigue values which the same material usually develops when used in the ordinary condition in the form of heat-treated rolled plates in laminated springs. Accordingly, the investigation has not led to safe stress determinations which can be directly applied to the design of normal laminated springs as now made, but the fatigue results represent what may be regarded as the intrinsic properties of the materials, and enable comparisons to be made on that basis. The immediate value of the work lies in showing that nearly all the steels investigated can be so heat-treated that they give a high resistance to bending fatigue, whereas the actual resistance of commercial heat-treated spring plates is low. This has led to an investigation, now in progress, of the factors which govern the fatigue failures of the commercial plates. A short discussion of the preliminary work of this further investigation is given at the end of the present paper.

LABORATORY TESTS ON STANDARD STEELS.

Materials.—The steels investigated were obtained mainly in the form of flat plates 3 in. by $\frac{3}{8}$ in. in section, and the tests were devised with a view to disclosing the mechanical properties when disturbing factors, such as surface blemishes and decarburisation, had been eliminated. The steels were supplied by leading firms of steel makers, and in addition to the flat plates small quantities of rolled bar from the same casts were available in most cases. The chemical analyses, together with the specifications to which the steels were supplied, are given in Table I. It will be noted that the 0.6 per cent. carbon steel and the two chromium steels fall within the British Engineering Standards analysis for spring steel plates. The nickel-chrome steel is not normally used as a spring steel, but was included in the investigation for a general comparison of results. Difficulty was experienced in obtaining uncracked water-quenched specimens of the 0.6 per cent. carbon steel, but some of the results obtained appear to be of sufficient interest to justify their inclusion in the present paper. In order

to obtain further information on the properties of a water-quenched carbon spring steel, the 0.46 per cent. carbon steel was included. This material was supplied as a typical spring steel which had proved satisfactory in the manufacture of water-quenched springs. It will be noted that both the carbon and manganese contents of this steel are below the specification limits for a carbon spring steel.

TABLE I.—*Analyses of Materials.*

Serial Number of Steel.	Designation.	Carbon. %	Silicon. %	Sulphur. %	Phosphorus. %	Manganese. %	Nickel. %	Chromium. %
S3	Low-chromium Specification	0.60	0.26	0.036	0.036	0.62	...	0.56
		0.55 to	0.50	0.06	0.05	0.50 to	...	0.45 to
		0.65				0.80		0.70
S4	High-chromium Specification	0.45	0.12	0.010	0.014	0.69	...	1.14
		0.45 to	0.50	0.06	0.05	0.50 to	...	1.0 to
		0.55				0.80		1.4
S7	Nickel-chromium	0.36	0.29	0.020	0.023	0.50	3.42	0.60
S1	0.6 per cent. carbon Specification	0.60	0.21	0.007	0.012	0.77	0.08	0.09
		0.50 to	0.50	0.06	0.05	0.60 to	...	...
		0.65				1.00		
S8	0.46 per cent. carbon	0.46	0.09	0.037	0.026	0.51	0.03	...

Note.—The specification figures for silicon, sulphur, and phosphorus are maximum values.

HEAT TREATMENT.

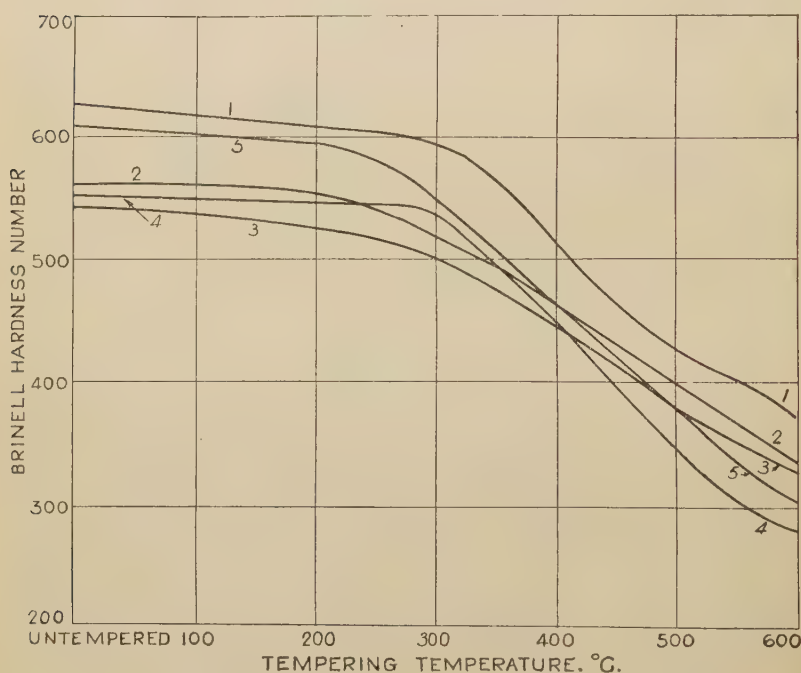
The methods used in the heat treatment were similar to those described in the previous paper, and it now suffices to say that the quenching temperatures were determined by a combination of thermal curves, microscopic examination of quenched specimens, and hardness tests. The desired hardening conditions were such that the resulting material possessed a martensitic structure, a high Brinell number, and did not show quenching cracks. Each material was subjected to a series of mechanical tests when drawn to three or four different tempering temperatures. Details of salient features in the heat-treatment experiments are given below.

(1) *Low-Chromium Steel.*—On the heating curve a marked arrest occurs at 760° C.; on the cooling curve a slight arrest occurs at 798° C., and a marked arrest at 711° C. Oil-quenching

of small pieces from 820° C. and 800° C. gave martensitic structures, Brinell numbers of over 600, and satisfactory uniformity of hardness. The results of hardness tests on 3-in. pieces of plate material, oil-quenched from 800° C. and tempered, are given in Table II. and in Fig. 1.

TABLE II.—3-in. Pieces Oil-Quenched from 800° C.

Tempering temperature. °C.	...	250	300	350	400	450	500	550	600
Brinell number . . .	630	620	590	580	510	450	430	415	365



1. Low-chromium spring steel, oil-quenched from 800° C.
2. High-chromium spring steel, oil-quenched from 820° C.
3. Nickel-chrome steel, oil-quenched from 820° C.
4. 0.46 per cent. carbon spring steel, water-quenched from 810° C.
5. 0.6 per cent. carbon spring steel, water-quenched from 800° C.

FIG. 1.—Tempering-Temperature/Brinell-Hardness Curves.

From these results it was decided to carry out mechanical tests on the material oil-quenched from 800° C. and tempered at each of the temperatures 400°, 500°, and 600° C.

The material showed a troosto-martensitic structure for each of these tempering temperatures; Fig. 7 (Plate XXIV.) shows a typical structure of the material after tempering at 500° C.

(2) *High-Chromium Steel*.—One arrest point was observed on the heating curve at 767° C., and two points, 780° C. and 717° C., were observed on the cooling curve. It was found that the oil-quenching of small pieces of this steel from 820° C. produced a martensitic structure and a Brinell hardness number of 565. Oil-quenching from 800° C. also produced a martensitic structure, but the resulting hardness was low, of the order of 440 Brinell. The results of hardness tests on 3-in. pieces, quenched from 820° C. and tempered, are given in Table III., and are shown in Fig. 1.

TABLE III.—3-in. Pieces Oil-Quenched from 820° C.

Tempering temperature. ° C.	...	250	300	350	400	450	500	550	600
Brinell number . . .	560	550	500	480	465	435	395	380	335

From the results of these experiments, it was decided to use a quenching temperature of 820° C., and tempering temperatures of 350°, 425°, 500°, and 575° C. Fig. 8 shows the structure of the material as oil-quenched from 820° C. and tempered at 500° C.

(3) *Nickel-Chromium Steel*.—On the heating and cooling curves the arrest points were not very definite, and, in order to find the temperature at which the ferrite was taken into solution, small pieces of the steel were quenched in oil from temperatures between 800° C. and 850° C. It was found that oil-quenching from 800° C. did not give a completely martensitic structure, but after heating at 820° C. for 15 min. and then quenching, the ferrite had disappeared and a martensitic structure was produced. The results of hardness tests on 3-in. pieces of the hardened and tempered material are given in Table IV. and are shown in Fig. 1. The pieces were quenched in water after tempering.

On account of the occurrence of temper-brittleness in some nickel-chromium steels, a series of notched-bar tests (Izod type)

was made on specimens cut from the above 3-in. pieces. It was not possible to prepare standard Izod specimens from these pieces, and 8-mm. by 8-mm. specimens were used, the notch in each case being a 45° notch, 1 mm. deep and 0.25 mm. root radius. The results of tests on these specimens in a standard 120-ft.-lb. Izod machine are given in Table IV., but, owing to the deviation of the notches from the normal standard dimensions, the results are comparative for this series only.

TABLE IV.—*Hardness and Comparative Notched-Bar Tests.*

Pieces oil-quenched from 820° C. (15 min. at 820° C.).

Tempering Temperature. ° C.	Brinell Number.	Energy Absorbed. Ft.-lb.			Mean Energy Absorbed. Ft.-lb.
...	537	9.2	7.8	9.2	8.7
250	515	11.2	11.0	11.2	11.1
300	505	8.5	8.6	9.2	8.8
350	480	4.5	4.5	4.9	4.6
400	455	4.4	5.2	5.0	4.9
450	410	10.0	9.2	10.8	10.0
500	365	20.7	22.0	23.1	21.9
550	358	24.0	26.4	26.8	25.7
600	335	31.0	30.4	31.0	30.8

The notched-bar results are low for tempering temperatures of 350° C. and 400° C., but there is no indication of brittleness at the higher tempering temperatures.

In view of the above results it was decided to adopt 820° C. as the quenching temperature of the material for the mechanical tests, and to maintain the pieces at that temperature for 15 min. before quenching. The tempering temperatures adopted were 350°, 400°, 450°, and 500° C. When normalised from 820° C. the structure of the material was partly sorbitic, and when quenched from 820° C. a fine martensite was obtained. Fig. 9 shows the structure after quenching from 820° C. and tempering at 400° C.

(4) 0.6 per cent. Carbon Steel.—Details of the heat treatment and mechanical properties of this material when oil-quenched have been given in the previous publication¹; the present experiments are concerned with the properties of the material when quenched in water.

¹ *Loc. cit.*

On the heating curve A_3 was absent, and a very slight arrest, probably A_{32} , occurred at 760°C. ; a well-marked arrest, A_1 , occurred at 729°C. On the cooling curve only one arrest, at 679°C. , was observed.

A large number of water-quenching experiments were carried out on 3-in. plates of this steel, using furnace temperatures of from 950°C. down to 800°C. , and quenching-water temperatures of from 18°C. up to 50°C. It was found that Brinell numbers from 650 to 700 could be obtained when the quenching-water temperature was 18°C. , but obvious hardening cracks were present. Higher temperatures of the quenching water gave lower proportions of cracked specimens, but also gave lower final hardness values and unevenly hardened material. Scale cracking in water before quenching did not appear to give appreciably greater uniformity. In general, it appeared that when the quenching and water temperatures were such that cracks were entirely eliminated, then incomplete and non-uniform hardening was obtained. Finally, however, a certain degree of success in the hardening was attained by quenching from 800°C. into water at 50°C. 3-in. plates quenched in this way showed no obvious cracks, and also gave Brinell numbers of the order of 600. Very small cracks may have been present in these specimens, however, since in three cases, although no cracks could be seen by the eye on a fine ground surface, when a ball impression was made on the surface fine cracks could be seen radiating outwards from the impression. Alternatively, it is possible that the internal stresses in the material were such that the extra stress set up by the ball test was sufficient to start the cracks, although no actual cracks may have been present before the hardness tests were made. If such were the case, the effect of tempering would be to relieve the internal stresses. Accordingly, a number of 3-in. plates were quenched from 800°C. into water at 50°C. , tempered at various temperatures, and then tested for hardness. The results obtained are given in Table V.

TABLE V.—3-in. Pieces Quenched from 800°C. into Water at 50°C.

Tempering temperature. $^\circ \text{C.}$	...	250	300	350	400	450	500	550	600
Brinell number . . .	610	590	550	490	475	430	380	350	300

No cracks were observed in any of these specimens, either before or after the hardness tests, and it was decided to attempt the treatment of plates for mechanical tests, using tempering temperatures of 400°, 450°, 500°, and 550° C. The pieces for the fatigue and Izod tests were in the form of 6-in. plates of the 3-in. by $\frac{3}{8}$ -in. section, and although uniformity of hardness was not very good on these pieces after treatment, no quenching cracks were apparent, and the usual fatigue and Izod specimens were prepared. The results of these tests are included in Tables VIII. and IX. The hardening and tempering treatment, however, was not satisfactory for the large tensile pieces, and hardening cracks occurred in most of the treated specimens. The cracks were not obvious on a ground surface, but the actual failures in the tensile tests showed that cracks were present, and the results were unreliable. After spoiling many specimens, the tensile tests were abandoned. Similarly, torsion test-pieces, prepared from $1\frac{1}{4}$ -in. diam. bar and then hardened and tempered, were also found to be cracked, and these tests were also abandoned. Apparently, the quenching treatment was satisfactory for 3-in. and 6-in. lengths, but not for 18-in. lengths or for prepared torsion specimens.

Fig. 10 (Plate XXV.) is a micrograph of the material when water-quenched from 800° C. and tempered at 450° C.; the structure is mainly martensitic.

(5) 0.46 per cent. Carbon Steel.—The thermal curves showed arrest points at 724° C. on the heating curve, and at 686° C. on the cooling curve.

Examination of small water-quenched specimens showed no signs of hardening cracks, but the uniformity of hardness was not good. After a number of trials, it was found that the best results were obtained by holding specimens at 810° C. for about 20 min. and then quenching in water at 20° to 25° C. This treatment produced a material with a martensitic structure, a Brinell number of 550 to 600, and no indications of cracks. The

TABLE VI.—3-in. Pieces Water-Quenched from 810° C.

Tempering temperature. ° C.	...	250	300	350	400	450	500	550	600
Brinell number . . .	550	540	540	490	450	390	340	310	280

TABLE VII.—*Results of Tensile Tests.*

Material.	Heat Treatment.	Brinell Number.	Limit of Proportionality. Tons per sq. in.	Yield Stress. Tons per sq. in.	Ultimate Stress. Tons per sq. in.	Extension on 8 in. %	Reduction of Area. %	Modulus of Elasticity. Lb. per sq. in.
	° C. ° F.							× 10 ⁸
Low - chromium steel	Normalised 815	274	31	...	55.3	10.3	35	30.8
	O.-Q. 800, T. 400	467	75	...	104.5	...	2	30.7
		471	78	...	108.3	2.5	2	30.6
		409	69	...	89.7	6.3	12	30.2
	O.-Q. 800, T. 500	417	68	...	90.5	5.0	11	30.5
		342	46	...	74.2	7.2	31	30.5
High - chromium steel	O.-Q. 800, T. 600	335	45	...	72.3	6.0	28	30.5
		250	34	40	53.9	12.5	50	30.3
	Normalised 830	480	70	...	100.5	...	1	29.9
	O.-Q. 830, T. 350	480	70	...	105.0	...	1	29.8
		450	70	94	100.2	4.3	13	29.8
	O.-Q. 830, T. 425	450	62	96	100.5	4.3	22	...
		390	63	78	84.5	6.3	32	30.0
	O.-Q. 830, T. 500	395	56	81	87.5	6.9	29	...
		350	47	69	73.9	8.6	36	30.1
	O.-Q. 830, T. 575	359	49	71	75.0	8.6	35	30.2
Normalised 820		304	25	45	66.0	11.2	31	30.1
Nickel-chromium steel	O.-Q. 820, T. 350	460	56	90	97.4	4.2	12	30.0
		460	55	89	98.7	4.2	12	30.2
	O.-Q. 820, T. 400	441	63	88	92.9	6.2	35	30.2
	O.-Q. 820, T. 450	404	60	86	88.9	6.9	35	30.4
	O.-Q. 820, T. 500	361	55	72	76.0	9.0	34	...
		370	54	73	76.0	9.2	32	30.1
0.46% carbon steel	Normalised 820	178	22	25	40.2	20.9	39	30.0
	W.-Q. 810, T. 400	380	42	62	83.3	4.2	...	...
		340	40	59	68.7	6.6	...	...
	W.-Q. 810, T. 450	350	40	...	74.3	4.2	...	...
		310	35	51	63.3	8.1	...	30.5
	W.-Q. 810, T. 500	300	39	56	63.9	7.2	...	30.2
		290	35	55	61.1	8.2	...	30.2
	W.-Q. 810, T. 550	280	30	45	57.6	10.2	...	30.2

O.-Q. = oil-quenched ; W.-Q. = water-quenched ; T. = tempered.

TABLE VIII.—*Results of Fatigue Tests.*

Material.	Heat Treatment.	Brinell Number.	Specimen.	Stress. Tons per sq. in.	Number of Reversals. (Millions.)	Estimated Fatigue Limit. Tons per sq. in.
Low-chromium steel	° C. ° C. O.-Q. 800, T. 400	520	S3I1C	± 56.5	0.08 B	± 48 to ± 52
			1B	± 55.2	0.14 B	
			1E	± 53.5	0.65 B	
			1F	± 52.2	0.05 B	
			1A	± 52.0	12.70 U	
			1D	± 49.1	0.15 B	
Low-chromium steel	O.-Q. 800, T. 500	435	S3I3A	± 46.7	0.10 B	± 43
			3B	± 44.0	0.21 B	
			3D	± 43.0	12.27 U	
			3C	± 41.6	10.21 U	
Low-chromium steel	O.-Q. 800, T. 600	368	S3I5A	± 43.2	0.15 B	± 38
			5B	± 40.8	0.09 B	
			5D	± 40.8	0.21 B	
			5E	± 39.2	0.92 B	
			5C	± 38.0	10.45 U	
High-chromium steel	O.-Q. 820, T. 350	474	S4J15E	± 52.5	0.06 B	± 50
			15A	± 52.2	0.08 B	
			15F	± 50.8	1.11 B	
			15D	± 49.1	12.61 U	
			15B	± 46.6	12.62 U	
High-chromium steel	O.-Q. 820, T. 425	438	S4J17E	± 48.3	0.35 B	± 45
			17A	± 48.0	0.59 B	
			17F	± 47.0	0.42 B	
			17D	± 45.9	10.05 U	
			17B	± 45.6	0.20 B	
			17C	± 44.5	10.15 U	
High-chromium steel	O.-Q. 820, T. 500	393	S4J19A	± 43.8	0.13 B	± 39
			19B	± 41.0	0.62 B	
			19D	± 40.1	1.03 B	
			19C	± 38.1	10.02 U	
High-chromium steel	O.-Q. 820, T. 575	343	S4J21F	± 42.1	0.46 B	± 38
			21E	± 39.4	10.36 U	
			21D	± 38.0	10.40 U	
			21A	± 37.8	0.21 B	
			21C	± 36.8	10.18 U	
			21B	± 35.4	5.78 U	
Nickel-chromium steel	O.-Q. 820, T. 350	481	S7D4B	± 52.0	0.12 B	± 51
			4D	± 52.0	0.36 B	
			4C	± 50.8	11.71 U	
			4A	± 49.4	10.19 U	
Nickel-chromium steel	O.-Q. 820, T. 400	438	S7L6E	± 48.0	0.21 B	± 46
			6F	± 46.6	4.42 U	
			6A	± 46.5	2.25 B	
			6D	± 45.0	10.42 U	
			6B	± 43.6	10.89 U	

O.-Q. = oil-quenched ; W.-Q. = water-quenched ; T. = tempered.
B. = broken ; U. = unbroken.

TABLE VIII. (*continued*).

Material.	Heat Treatment.	Brinell Number.	Specimen.	Stress. Tons per sq. in.	Number of Reversals. (Millions.)	Estimated Fatigue Limit. Tons per sq. in.
	$^{\circ}\text{C.}$ $^{\circ}\text{F.}$					
Nickel-chromium steel	O.-Q. 820, T. 450	406	<i>S7L8F</i>	± 45.0	12.27 U	
			8A	± 44.5	1.79 B	
			8E	± 43.8	10.13 U	
			8B	± 43.2	0.74 B	± 42
			8C	± 42.2	0.15 B	to
			8D	± 41.9	10.26 U	± 45
Nickel-chromium steel	O.-Q. 820, T. 500	378	<i>S7L10B</i>	± 44.5	0.09 B	
			10C	± 44.0	0.32 B	
			10D	± 41.9	13.48 U	
			10A	± 40.5	10.52 U	± 42
0.6% carbon steel	W.-Q. 800, T. 400	460	<i>S1H10B</i>	± 51.0	0.18 B	
			10A	± 46.7	0.05 B	
			10D	± 46.7	0.04 B	
			10E	± 46.0	0.15 B	
			10F	± 44.0	15.81 U	
			10C	± 38.6	11.58 U	± 45
0.6% carbon steel	W.-Q. 800, T. 450	415	<i>S1H12A</i>	± 42.6	0.27 B	
			12C	± 41.0	0.51 B	
			12D	± 40.6	0.35 B	
			12F	± 38.6	5.38 U	
			12B	± 37.2	16.33 U	± 39
0.6% carbon steel	W.-Q. 800, T. 550	350	<i>S1H16B</i>	± 38.6	0.82 B	
			16C	± 37.5	0.33 B	
			16D	± 37.5	8.75 U	
			16A	± 36.0	17.47 U	± 37
0.46% carbon steel	W.-Q. 810, T. 400	435	<i>S8B5A</i>	± 43.3	0.09 B	
			5B	± 41.3	0.10 B	
			5F	± 38.2	0.21 B	
			5C	± 37.3	0.12 B	
			5E	± 35.9	10.19 U	
			5D	± 34.6	10.56 U	± 36
0.46% carbon steel	W.-Q. 810, T. 450	370	<i>S8B6D</i>	± 40.7	0.11 B	
			6E	± 39.4	0.25 B	
			6F	± 38.6	0.10 B	
			6C	± 38.0	11.79 U	
			6B	± 36.6	0.58 B	± 35 to
			6A	± 34.0	11.80 U	± 38
0.46% carbon steel	W.-Q. 810, T. 500	320	<i>S8B7D</i>	± 38.6	0.17 B	
			7C	± 38.0	0.20 B	
			7B	± 37.2	0.22 B	
			7A	± 35.6	10.01 U	
			7F	± 33.2	12.30 U	± 36
0.46% carbon steel	W.-Q. 810, T. 550	300	<i>S8B8B</i>	± 33.2	0.14 B	
			8C	± 33.2	0.49 B	
			8D	± 32.9	0.35 B	
			8F	± 32.9	18.45 U	
			8E	± 31.9	10.09 U	
			8A	± 30.6	12.45 U	± 33

O.-Q. = oil-quenched; W.-Q. = water-quenched; T. = tempered.
B. = broken; U. = unbroken.

uniformity of hardness, however, was not so good as that obtained in oil-quenched spring steels. The mean results of hardness tests on 3-in. pieces subjected to the above water-quenching treatment and then tempered are given in Table VI. (p. 224).

From the results of the above experiments it was decided to use 810° C. as the quenching temperature of the material for the mechanical tests, holding the plates at this temperature for 20 min., and to use tempering temperatures of 400°, 450°, 500°, and 550° C.

A typical structure of the hardened and tempered material is shown in Fig. 11, but patches of softer material also occurred. A region, typical of the softer patches, is shown in Fig. 12.

MECHANICAL TESTS.

Tensile, fatigue, Izod, and torsion tests were made on the hardened and tempered materials, and in all cases the test methods were the same as those described in the previous paper.

Tensile Tests.—The results of the tensile tests are given in Table VII. (p. 225); it should be noted that the complete length of a specimen was 18½ in., and that the gauge length of 8 in. was adopted in accordance with the standard form, in which

$$\text{gauge length} = 11.3\sqrt{(\text{cross-sectional area})}.$$

In the case of the high-chromium steel it was found that the hardness values in the tensile test-pieces after heat treatment were lower than those given in Table III., and a quenching temperature of 830° C. was used for these large specimens.

Fatigue Tests.—The fatigue tests were made by the endurance method on rotating cantilever specimens running at 2000 to 2500 r.p.m. Each batch of specimens was cut out from a 6-in. length of the 3-in. by ¾-in. plate after heat treatment, and each specimen was ground to size and then polished. The results of the tests are given in Table VIII. (pp. 226–227).

Notched-Bar Impact Tests.—The tests were made by the Izod method in a standard 120-ft.-lb. machine. The cross-sections of the specimens were 9 mm. by 9 mm., as in the previous tests, and the notch had an angle of 45° with a depth of 1 mm., and 0.25 mm. root radius. The results of the tests are given in Table IX.

TABLE IX.—*Results of Notched-Bar Impact Tests.*

Material.	Heat Treatment.	Brinell Number.	Energy Absorbed.			Mean Energy Absorbed. Ft.-lb.
			Ft.-lb.			
Low-chromium steel	° C. ° C. O.-Q. 800, T. 400	514	2.3	2.6	2.5	2.2
	O.-Q. 800, T. 500	438	2.0	2.0	2.0	
	O.-Q. 800, T. 600	363	10.9	8.3	8.6	9.0
			8.6	8.0	9.9	
High-chromium steel	O.-Q. 820, T. 350	500	23.7	23.0	20.5	22.5
	O.-Q. 820, T. 425	450	22.0	22.0	24.0	
	O.-Q. 820, T. 500	410	9.0	10.9	17.0	11.8
			13.2	10.1	10.8	
	O.-Q. 820, T. 575	350	12.9	12.4	12.9	12.3
			12.1	11.0	12.2	
Nickel-chromium steel	O.-Q. 820, T. 350	477	20.0	18.6	11.9	16.9
	O.-Q. 820, T. 400	448	16.2	17.8	17.0	
	O.-Q. 820, T. 450	426	53.2	48.1	53.2	50.1
	O.-Q. 820, T. 500	375	47.7	52.0	46.7	
	O.-Q. 820, T. 575	350	6.5	4.0	4.3	4.9
			5.0	3.4	6.5	
0.6% carbon steel	W.-Q. 800, T. 400	470	5.8	6.2	4.1	5.6
	W.-Q. 800, T. 450	416	6.2	5.8	5.5	
	W.-Q. 800, T. 500	360	12.0	11.9	11.1	11.7
	W.-Q. 800, T. 550	340	12.0	10.9	12.5	
	W.-Q. 810, T. 400	400	20.0	26.2	23.1	23.7
	W.-Q. 810, T. 450	370	25.5	25.5	21.9	
0.46% carbon steel	W.-Q. 810, T. 500	320	8.0	9.0	8.0	8.4
	W.-Q. 810, T. 550	295	8.4	8.9	8.4	
	W.-Q. 820, T. 350	500	11.0	13.1	11.1	11.9
	W.-Q. 820, T. 425	450	13.0	11.5	12.0	
	W.-Q. 820, T. 500	410	26.0	25.0	22.7	24.8
	W.-Q. 820, T. 575	350	23.6	27.5	23.9	
0.46% carbon steel	W.-Q. 820, T. 600	363	28.3	33.0	24.1	27.5
	W.-Q. 820, T. 650	338	23.2	32.4	24.3	
	W.-Q. 830, T. 400	400	3.8	4.0	3.0	3.5
	W.-Q. 830, T. 450	370	3.9	3.0	3.0	
	W.-Q. 830, T. 500	320	10.5	17.0	16.1	14.7
	W.-Q. 830, T. 550	295	13.8	12.7	17.9	
0.46% carbon steel	W.-Q. 830, T. 600	363	26.8	31.3	17.8	23.2
	W.-Q. 830, T. 650	338	22.5	25.7	15.0	
	W.-Q. 840, T. 400	400	4.5	39.1	41.5	34.2
	W.-Q. 840, T. 450	370	30.0	23.0	37.4	
	W.-Q. 840, T. 500	320				(mean of 5)
	W.-Q. 840, T. 550	295				

O.-Q. = oil-quenched ; W.-Q. = water-quenched ; T. = tempered.

Torsion Tests.—Torsion tests were made on the two chromium steels and on the nickel-chromium steel; the results obtained are given in Table X.

TABLE X.—*Results of Torsion Tests.*

Material.	Heat Treatment.	Brinell Number.	Limit of Proportionality. Tons per sq. in.	Ultimate Modulus of Rupture. Tons per sq. in.	Modulus of Rigidity. Lb. per sq. in.	Total Angle of Twist in 4 in. Degrees.
	° C. ° C.				× 10 ⁶	
Low-chromium steel	O.-Q. 800, T. 400 {	506	51	89.0	11.9	584
		510	52	89.0	12.2	585
	O.-Q. 800, T. 500 {	435	46	71.2	12.0	878
		433	43	71.5	12.2	901
	O.-Q. 800, T. 600 {	361	36	60.9	12.2	1103
		356	34	59.8	12.0	934
High-chromium steel	O.-Q. 820, T. 350 {	464	53	89.6	11.3	256
		477	53	89.7	11.4	261
	O.-Q. 820, T. 425 {	448	52	83.0	11.4	203
		438	51	83.1	11.5	203
	O.-Q. 820, T. 500 {	385	44	69.9	11.4	562
		385	42	70.6	11.4	609
	O.-Q. 820, T. 575 {	339	35	64.3	11.5	774
		335	35	64.3	11.6	1014
Nickel-chromium steel	O.-Q. 820, T. 350 {	474	48	82.8	11.4	639
		460	48	82.5	11.3	...
	O.-Q. 820, T. 400 {	429	45	74.2	11.3	786
		420	46	73.5	11.5	816
	O.-Q. 820, T. 450 {	406	44	68.5	11.6	1004
		404	44	69.1	11.6	1026
	O.-Q. 820, T. 500 {	366	41	62.9	11.7	1331
		366	41	63.8	11.7	1596

O.-Q. = oil-quenched; T. = tempered.

The results of the tests are summarised in Fig. 1, which gives the Brinell-number/tempering-temperature relationship, and in Figs. 2, 3, 4, 5, and 6, which show the mean results of some of the mechanical tests. The following brief comments on the properties of the individual steels appear to be justified.

Low-Chromium Steel (Fig. 2).—The fatigue limit values obtained with this steel are slightly below the mean values obtained from the other oil-quenched spring steels. The general mechanical properties appear to be somewhat similar to those of the oil-quenched 0.6 per cent. carbon steel (see previous paper), the Izod values and reduction of area figures being below those of the other steels containing chromium. There was some

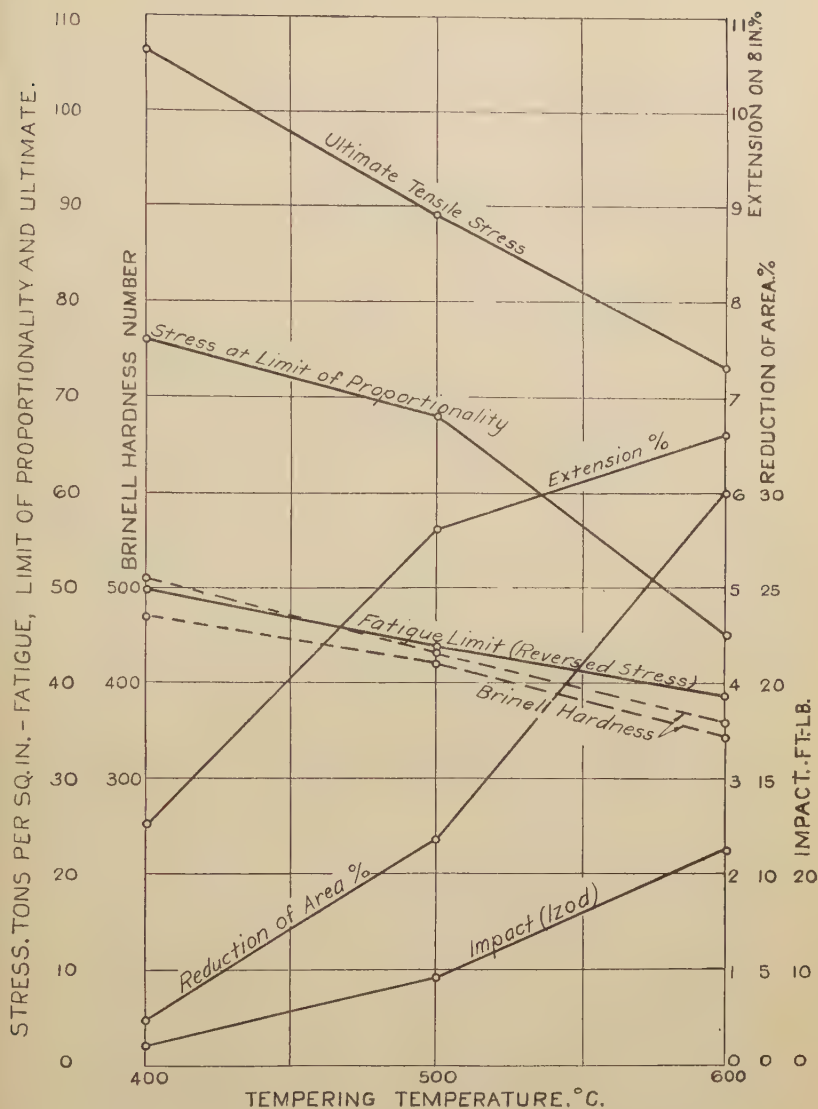


FIG. 2.—Tests on Low-Chromium Spring Steel, oil-hardened from 800° C.

evidence that mass effect in the quenching operation was more marked in this steel than in the others.

High-Chromium Steel (Fig. 3).—The fatigue limit values obtained on this steel are about the same as the mean values obtained from the other oil-quenched steels. The reduction of area is low at the lowest tempering temperature, but there is a very marked increase with an increase in the tempering temperature. The Izod figure corresponding to the Brinell hardness 350, namely, 50 ft.-lb., is the highest value obtained in the whole series of tests.

Nickel-Chrome Steel (Fig. 4).—This material is not usually regarded as a spring steel, but the mechanical properties developed in the tests do not show any very marked differences from those given by spring steels. The fatigue limit of the material when tempered at 350° C. (Brinell hardness number 480) is ± 51 tons per sq. in., and this is the highest value which has been obtained in the present series of tests, but, considering all four fatigue determinations, the values are very similar to those obtained with silico-manganese steel tempered to the same Brinell hardness. The tensile limit of proportionality of the steel when tempered at 350° C. is low in comparison with the spring steels. The reduction of area figures at the higher tempering temperatures are good, but the Izod values at the lower tempering temperatures are low.

0.6 per cent. Carbon Steel, Water-Quenched (Fig. 5).—In considering these results, it should be borne in mind that great difficulty was experienced in obtaining uniform specimens free from hardening cracks, but it appears that when such material is obtained the mechanical properties are quite good. The fatigue limit values are only slightly inferior to those given by the alloy steels, and to those for the same material when oil-quenched from 950° C. The Izod values corresponding to the Brinell hardness 350 are superior to those given by the same material oil-quenched, or by the silico-manganese steel, either oil- or water-quenched. Both fatigue limit and Izod values of the water-quenched 0.6 per cent. carbon steel are superior to those of the water-quenched 0.46 per cent. carbon steel tempered to the same Brinell hardness. The liability to cracking, however, appears to be a drawback to the use of the steel after water-

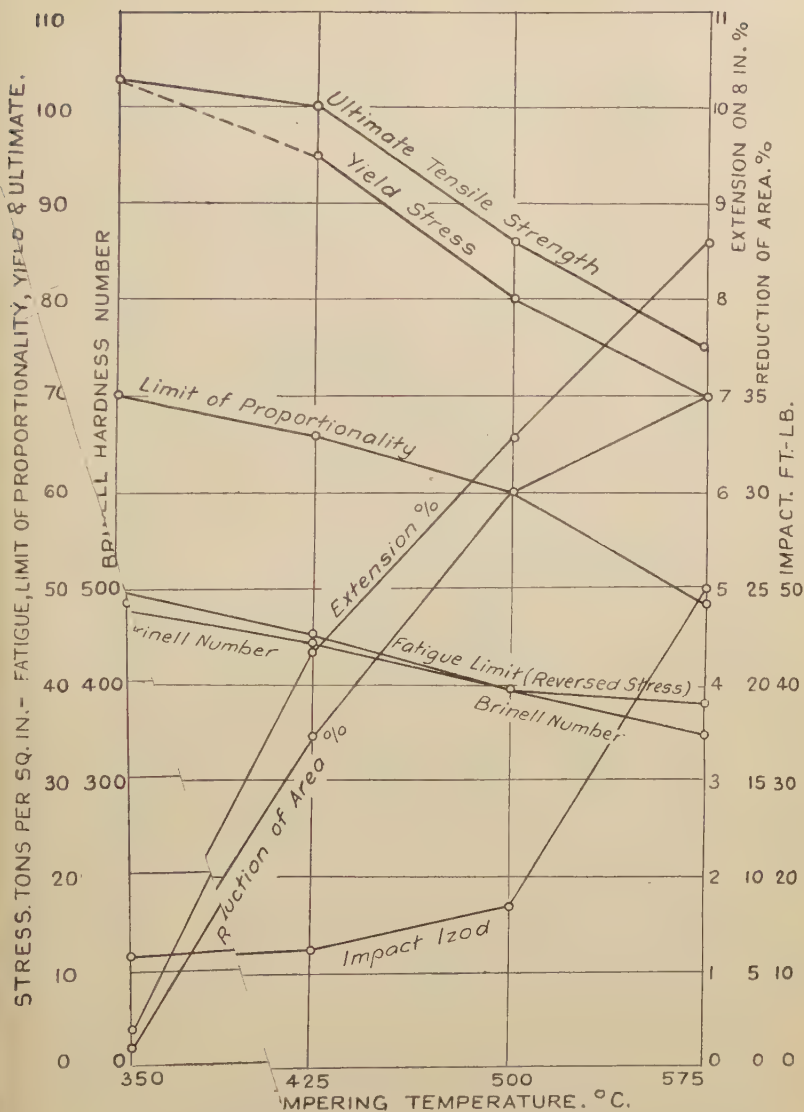


FIG. 3.—Tests of High-Chromium Spring Steel, oil-quenched from 820° to 830° C.

quenching; the experience obtained in the tests suggests that water-quenching from about 800°C. and above may produce

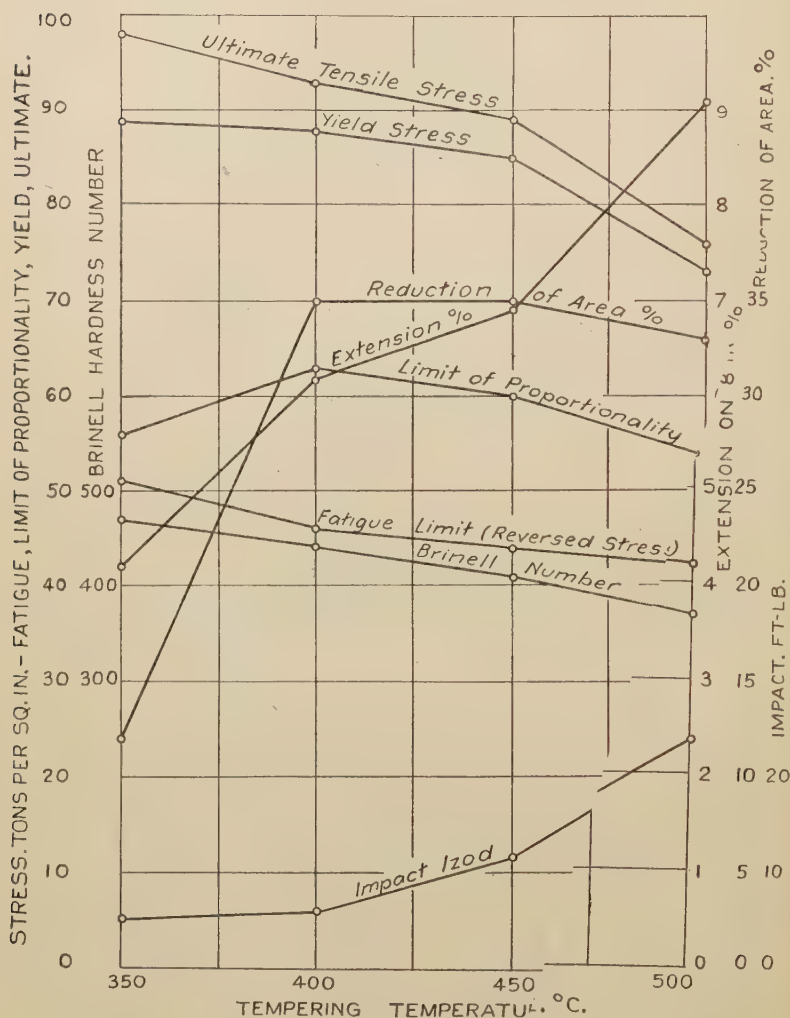


FIG. 4.—Tests on Nickel-Chrome Steel, oil-hardened from 820°C.

hardening cracks which are not detected by scragging tests on finished springs. Quenching at lower temperatures may enable

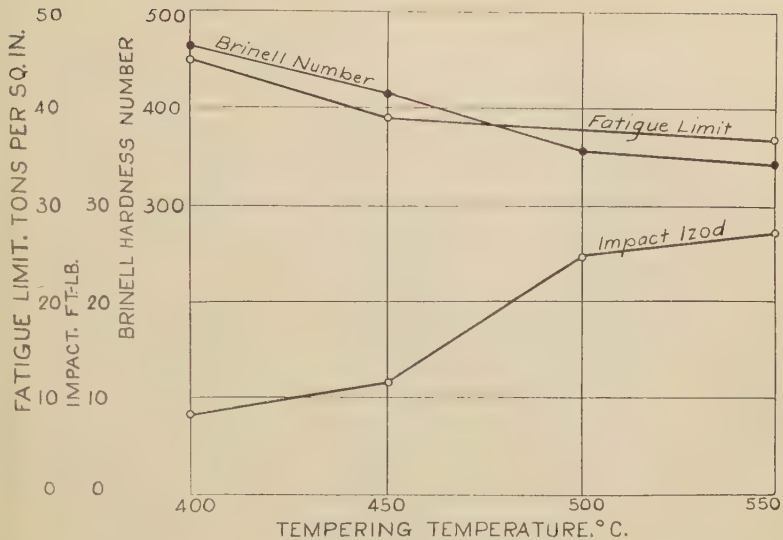


FIG. 5.—Tests on 0.6 per cent. Carbon Steel, water-quenched from 800° C.

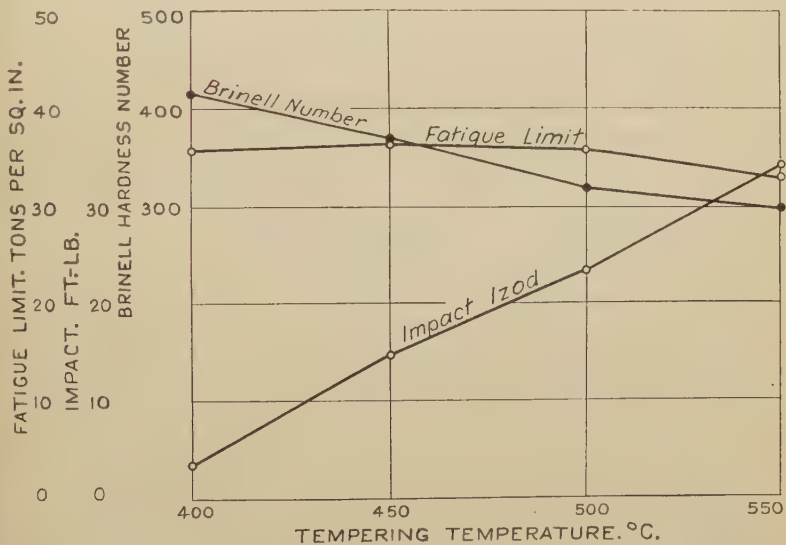


FIG. 6.—Tests on 0.46 per cent. Carbon Steel, water-quenched from 810° C.

uncracked springs to be obtained, the material then being in a toughened condition, but the present experiments suggest that a considerable lack of uniformity is likely to occur when the steel is quenched in this way.

0.46 per cent. Carbon Steel, Water-Quenched (Fig. 6).—The water-quenching did not produce cracked material, but variations in hardness occurred in specimens which were subjected to the same heat treatments. Since similar methods of heat treatment were used throughout the whole investigation, it may be concluded that the 0.46 per cent. carbon steel when water-quenched is likely to be more variable than any of the other steels when similar methods are used in the hardening and tempering operations. The fatigue limit values of the material are lower than the values given by the other steels when tempered to the same Brinell hardness. The results suggest that a tempering temperature of 500° C., giving a Brinell number of about 320, is the most suitable treatment of the quenched material for satisfactory use in practice. The Izod value corresponding to this treatment is of the order of 23 ft.-lb., and is thus fairly good for a carbon steel.

GENERAL DISCUSSION OF THE RESULTS OF THE COMPLETE INVESTIGATION.

A general comparison of results, including those given in the previous paper, can now be made. It must be remembered, however, that the results represent the properties of the materials as revealed by laboratory tests on prepared polished specimens, and that the fatigue limits obtained are much higher than would ordinarily be given by spring plates or wires in the normal condition in which they are used in practice.

A comparison of the properties of the steels can be made by plotting the results of each particular test against the Brinell numbers, but the diagrams obtained are rather complicated. A more convenient general comparison is obtained by grouping the results in the manner shown in Table XI. The fatigue limit, the tensile limit of proportionality, and the Izod value were selected for comparison as the most important properties on which to estimate the value of a spring steel. A high fatigue limit is necessary for the spring to withstand repetitions of high

stress without breaking. A high initial proportional limit minimises any permanent set and "settling down" of the spring in use. The Izod result indicates the resistance which the material offers to deformation under highly localised stresses and to the growth of a crack, and shows whether or not the material has been heat-treated in the best possible manner. The result is of relative significance only, but experience in general engineering work has shown that a good Izod value is desirable for satisfactory service in heat-treated steels. The values of the various properties given in Table XI. were obtained from curves of the results plotted against the corresponding Brinell numbers. The behaviour of some of these materials under torsional fatigue has been considered in detail elsewhere,¹ and it is not proposed to discuss the results in the present paper. The results of static torsion tests, however, are summarised in Table XII. It will be noted that the ratio of the nominal ultimate torsional strength to the Brinell number varies from 0.16 to 0.19, whereas the tensile tests, with very few exceptions, show the usual approximately constant ratio of tensile strength to Brinell number.

Considering the fatigue limit values, given in Table XI., and omitting the 0.46 per cent. carbon steel, the tests show that the endurance fatigue limit of any particular steel and heat treatment is closely related to the tensile strength and Brinell number, and is little affected by the composition of the steel. Thirty-three fatigue limit determinations have been made on these steels, and the ratio of the fatigue limit in tons per square inch to the Brinell number varies within the comparatively narrow range of 0.091 to 0.115, with a total mean value of 0.105. The higher Brinell numbers usually correspond to the lower values of the ratios, but this is not always the case. It appears that the endurance fatigue limit (rotating cantilever method) of a spring steel possessing a Brinell number between 320 and 500, and a martensitic structure, can be estimated roughly from the approximate rule that the fatigue limit in tons per square inch is one-tenth of the standard Brinell number. In general, the tests show that high-grade steels falling within each of the specification limits can be heat-treated to give a satisfactory resistance to bending fatigue with polished specimens, and that any differences in

¹ *Engineering Research Board, Special Report, No. 9.*

TABLE XI.—Comparison of Mechanical Properties of Hardened and Tempered Spring Steels.

Steel.	Quenching Treatment.	Group 1. Brinell Number = 350.			Group 2. Brinell Number = 410.			Group 3. Brinell Number = 470.			Mean Modulus of Elasticity. Lb. per sq. in.
		Fatigue Limit. Tons per sq. in.	Tensile Limit of Proportionality. Tons per sq. in.	Izod Value. Ft.-lb.	Fatigue Limit. Tons per sq. in.	Tensile Limit of Proportionality. Tons per sq. in.	Izod Value. Ft.-lb.	Fatigue Limit. Tons per sq. in.	Tensile Limit of Proportionality. Tons per sq. in.	Izod Value. Ft.-lb.	
0.6% carbon .	[°] C. O.-Q. 950	± 38	53	19	± 41	59	13	± 48	68	2	× 10 ⁸ 29.9
0.6% carbon .	W.-Q. 800	± 37	...	27	± 39	...	12	± 46	...	8	...
0.8% carbon .	O.-Q. 900	± 39	37	12	...	...	...	...	...	...	30.1
Low-chromium .	O.-Q. 800	± 38	48	23	± 42	68	14	± 47	76	5	30.5
High-chromium .	O.-Q. 820	± 38	48	50	± 41	62	17	± 50	70	12	30.0
Chrome-vanadium .	O.-Q. 850	± 41	50	45 ¹	± 43	63	23	± 44	70	13	30.3
Silico-manganese .	O.-Q. 950	± 39	51	17	± 46	61	12	± 48	68	9	30.1
Silico-manganese .	W.-Q. 870	± 39	54	19	± 46	70	14	± 50	83	11	30.1
Nickel-chrome .	O.-Q. 820	± 41	53	30 ¹	± 44	61	15	± 50	60	5	30.2
0.46% carbon .	W.-Q. 810	± 36	40	17	± 36	44 ¹	3	...	...	...	...

O.-Q. = oil-quenched; W.-Q. = water-quenched.

¹ Approximate.

TABLE XII.—Comparison of Torsion Test Results on Hardened and Tempered Spring Steels.

Steel.	Quenching Treatment.	Group 1. Brinell Number = 350.			Group 2. Brinell Number = 410.			Group 3. Brinell Number = 470.			Mean Modulus of Rigidity. Lb. per sq. in.
		Torsional Limit of Proportionality. Tons per sq. in.	Torsional Ultimate Modulus of Rupture. Tons per sq. in.	Ratio of Torsional Ultimate Modulus to Brinell Number.	Torsional Limit of Proportionality. Tons per sq. in.	Torsional Ultimate Modulus of Rupture. Tons per sq. in.	Ratio of Torsional Ultimate Modulus to Brinell Number.	Torsional Limit of Proportionality. Tons per sq. in.	Torsional Ultimate Modulus of Rupture. Tons per sq. in.	Ratio of Torsional Ultimate Modulus to Brinell Number.	
	° C.										× 10 ⁶
0.6% carbon .	O.-Q. 950	35	63	0.18	43	73	0.18	...	...	...	11.7
0.8% carbon .	O.-Q. 900	32	67	0.19	...	...	...	...	...	...	11.6
Low-chromium .	O.-Q. 800	34	59	0.17	43	68	0.17	49	83	0.18	12.1
High-chromium .	O.-Q. 820	38	67	0.19	47	77	0.19	53	89	0.19	11.4
Chrome-vanadium .	O.-Q. 850	...	...	...	42	67	0.16	52	80	0.17	11.7
Silico-manganese .	O.-Q. 950	38	67	0.19	47	77	0.19	53	86	0.18	11.6
Silico-manganese .	W.-Q. 870	41	68	0.19	49	77	0.19	60	89	0.19	11.5
Nickel-chrome .	O.-Q. 820	39	60	0.17	44	70	0.17	48	82	0.17	11.5

O.-Q. = oil-quenched; W.-Q. = water-quenched.

behaviour in practice in regard to failure by fatigue cannot be attributed to low fatigue limits inherent in the steels and heat treatments, provided, of course, that the heat treatment has not produced cracks. A typical nickel-chrome steel, which is not usually regarded as a spring steel, gives fatigue values which are very similar to those obtained with the spring steels. It does not follow that the approximate equality of several of the steels in resistance to fatigue would also hold for plates or wires in which unknown disturbing surface factors were present; the present fatigue determinations form an essential preliminary, however, to a detailed examination of the surface defects. The 0.46 per cent. carbon spring steel cannot be included in the above generalisations, but even this steel can be water-quenched and tempered to give an endurance fatigue limit of ± 36 tons per sq. in., and an endurance-limit/Brinell-number ratio of over 0.10. At low tempering temperatures, however, giving a Brinell number of 450, the ratio is down to 0.079 for this steel. This result, combined with the low ductility and lack of uniformity, suggests that it is advisable to temper straight carbon spring steel so that the resulting material does not give a Brinell number in excess of 370.

In the present investigation the fatigue tests were carried out on a ten million endurance basis, but a detailed examination of the results of the 37 bending fatigue limit determinations on all the steels shows that identical results would have been obtained in 25 cases if the tests had been made on a one million endurance basis. The remaining determinations would have given slightly higher values on the lower endurance basis. It appears that endurance fatigue tests on polished specimens of spring steels would be sufficiently accurate for practical purposes if carried out on a two million endurance basis.

Considering the tensile limit of proportionality figures given in Table XI., three results are rather outstanding—namely, the low values given by the 0.8 per cent. and the 0.46 per cent. carbon steels, and the high value given by the water-quenched silico-manganese steel in group 3. In general, the proportional limits increase with increasing tensile strength and Brinell number, but variations are much more marked than for the fatigue limits. It should be noted that the silico-manganese steel when water-



FIG. 7.—Low-chromium steel, oil-quenched from 800°C. , tempered at 500°C. $\times 300$.



FIG. 8.—High-chromium steel, oil-quenched from 820°C. , tempered at 500°C. $\times 400$.



FIG. 9.—Nickel-chromium steel, oil-quenched from 820°C. , tempered at 400°C. $\times 300$.

The above micrographs have been reduced to two-thirds linear in reproduction.



FIG. 10.—0.6 per cent. carbon steel, water-quenched from 800° C., tempered at 450° C. $\times 400$.



FIG. 11.—0.46 per cent. carbon steel, water-quenched from 810° C., tempered at 550° C. $\times 300$.



FIG. 12.—0.46 per cent. carbon steel, water-quenched from 810° C., tempered at 500° C. $\times 600$.

The above micrographs have been reduced to two-thirds linear in reproduction.

quenched gives the highest value for the proportional limit in each of the three groups.

For each steel the Izod figures decrease with increasing tensile strength and Brinell number, but wide differences occur in the results given by the various steels. At present no definite indication can be given as to the exact significance of the Izod figure in assessing the value of a spring steel, but, other things being equal, the steel possessing the highest Izod value appears to be the best one to select for a spring. Apparently, spring failures in practice are often due to stress concentrations at the bottom of small cracks or other surface discontinuities, and the suggestion may be made that a steel possessing a low Izod value is more likely to be seriously influenced by such defects than one possessing a high Izod value. In group 1 of Table XI. several of the steels show good Izod values, particularly the high-chromium and chrome-vanadium steels; in group 2 the chrome-vanadium steel is superior to all the others; in group 3 all the Izod figures are low, and the values obtained with the silico-manganese steels are very little less than those given by the chrome-vanadium steel.

Considering the fatigue limit, the proportional limit, and the Izod values, attention may be drawn to the good combination of properties exhibited by the chrome-vanadium steel in group 1, and the water-quenched silico-manganese steel in group 3. On the basis of the present results the 0.46 per cent. carbon steel, water-quenched, is definitely inferior to the alloy steels and to the 0.6 per cent. carbon steel, oil-quenched from 950° C.

The elastic moduli determinations are fairly constant for each steel, irrespective of the heat treatment, and, except for the low-chromium steel, the mean values for all the steels are about the same. Excluding the low-chromium steel, sixty-two determinations of the tensile modulus of elasticity were made, and the results vary from 29.5×10^6 to 30.9×10^6 lb. per sq. in., with a total mean value of 30.1×10^6 lb. per sq. in. Similarly, the modulus of rigidity varies from 11.3×10^6 to 11.9×10^6 lb. per sq. in., with a total mean value of 11.6×10^6 lb. per sq. in. For the low-chromium steel the mean values of both the modulus of elasticity and the modulus of rigidity are slightly higher than the mean values given by all the other steels (see Tables XI.

and XII.). It is considered that many of the variations from the mean given in the detailed results are greater than the probable experimental error (this is undoubtedly the case in regard to the low-chromium steel); for normal design purposes, however, it is suggested that the values 30.1×10^6 lb. per sq. in. and 11.6×10^6 lb. per sq. in. for the two elastic constants may be used with safety for all spring steels, irrespective of composition or heat treatment.

SURFACE CONDITION AND FATIGUE OF SPRING STEELS.

The fatigue tests described in the present paper have been confined to experiments on carefully prepared polished specimens. In the usual form of laminated spring, however, the material is in the form of heat-treated rolled plates, and it should be noted that fatigue tests carried out by one of the authors on rolled spring plates¹ have given endurance limits much lower than those obtained on the present polished specimens. The difference appears to be largely due to the surface condition of the material. In the normal commercial spring plate there is usually a thin layer of decarburised material at the surface, and it is known that this surface layer is softer than the main body of the plate. Since the present investigation has shown that the real fatigue resistance of a spring steel varies with the hardness, the fatigue limit of the surface layer is less than that of the inner portion of the plate. In addition, the surface of the plate is not plane, but usually contains small irregularities of shape, such as small pits, lines, and scratches, which would also reduce the effective resistance to alternating or repeated stresses. It must also be remembered that the bending moments on a spring plate cause the highest stresses to occur at the skin, and, accordingly, the presence of a decarburised surface layer containing small irregularities of shape is highly conducive to the initiation of fatigue cracks at stresses much below the real fatigue limit of the main body of the material. When a crack has been formed at the skin, the high stress concentration at the root of the crack would be sufficient to cause it to extend itself into the sound material of the middle portion, and so complete failure of the plate occurs. Some

¹ *Engineering Research, Special Report, No. 5.*

indication of the magnitude of the lowered resistance to fatigue caused by surface conditions can be obtained from the following figures.

Rotating cantilever fatigue tests, in which the specimens were ground and polished to size and then heat-treated, were made on the chrome-vanadium and silico-manganese spring steels. The specimens were then tested in this condition without any further machining or polishing; the results obtained are given in Table XIII.

TABLE XIII.—*Rotating Cantilever Tests on Heat-Treated Unpolished Specimens.*

Material.	Heat Treatment.	Specimen.	Stress. Tons per sq. in.	Number of Reversals. (Millions.)	Estimated Fatigue Limit. Tons per sq. in.
Silico-manganese steel	° C. ° O. O.-Q. 950, T. 500	S6Q1A	± 44.0	0.07 B.	± 27
		1B	± 38.6	0.13 B.	
		1C	± 33.2	0.61 B	
		1E	± 31.1	0.46 B.	
		1D	± 27.8	4.17 B.	
		1F	± 26.5	10.77 U.	
Chrome-vanadium steel	O.-Q. 850, T. 600	S5K1B	± 38.3	0.09 B.	± 32
		1A	± 33.0	2.51 B.	
		1D	± 31.8	14.15 U.	
		1C	± 30.3	10.77 U.	

O.-Q. = oil-quenched; T. = tempered; B. = broken; U. = unbroken.

The previous tests on polished specimens of these materials with the same heat treatments gave values of ± 46 and ± 42.5 tons per sq. in. for the silico-manganese steel and chrome-vanadium steel, respectively. Hence the surface defects arising in the heat treatments have caused marked decreases in the resistance to fatigue.

In the case of the 0.6 per cent. carbon spring steel, complete laminated springs were made up from this material after rolling the original 3 in. by $\frac{3}{8}$ -in. plates down to 2 in. by $\frac{1}{4}$ -in. section. The results of fatigue tests on the complete springs have been published elsewhere,¹ and it is shown that the fatigue limit of

¹ *Engineering Research, Special Reports*, Nos. 11 and 13.

the material in the springs was of the order of 0 to 20 tons per sq. in. safe range of stress. The fatigue limit of the same material with the same heat treatment was ± 38 tons per sq. in.—that is, a range of 76 tons per sq. in.—when tested in the form of prepared polished test-pieces. Endurance tests of complete springs of chrome-vanadium steel and silico-manganese steel were also made, and none of these springs gave safe ranges of stress greater than 20 tons per sq. in., although from the results of the present investigation it is reasonable to suppose that the fatigue limits of the actual materials were of the order of ± 40 tons per sq. in. Apparently, the surface condition is the predominating factor in causing the fatigue resistance of the complete springs to be so much below that of the actual material.

More detailed investigation of these disturbing surface factors is now in progress, but sufficient has been said to show their importance in the resistance of spring plates to fatigue. At present all that can be said in regard to remedies is that surface irregularities in manufacture should be avoided as far as possible, and that decarburisation should be reduced to a minimum. Complete surface grinding and polishing of spring plates after the final heat treatment is hardly feasible, but in special cases it may be worthy of consideration. Surface grinding of the plates after rolling and before heat treatment would probably be beneficial, but the results recorded in Table XIII. show that even this process would not enable the full resistance of the material to be utilised.

The authors desire to acknowledge the advice and encouragement received from Dr. W. Rosenhain, F.R.S., Chairman, and from the members of Panel No. 1 of the Springs Research Committee; they are also indebted to Professor D. Hanson, D.Sc., for assistance during the earlier stages of the investigation.

DISCUSSION.

Dr. T. SWINDEN (Sheffield) emphasised the value of the authors' work to those engaged in the production of springs. It was very striking that the net result of the work on endurance fatigue limits could be reduced to such a simple formula as one-tenth of the Brinell hardness number. One sentence on p. 241—namely, that “spring failures in practice are often due to stress concentrations at the bottom of small cracks or other surface discontinuities”—did not, however, quite coincide with his own experience. That was a fairly common experience in the case of coil springs, but so far as he knew it was not so common in the case of laminated springs. Most of the latter failures took place through pure fatigue cracks, or were due to shock. The question of determining the type of steel which would be most satisfactory and economical in use in a certain type of spring must be decided by considering whether a high fatigue limit or a high resistance to shock were the more important factor. The concluding portion of the paper on “Surface Condition” was very striking and somewhat disturbing. It was in line with other work which had been published on the same subject, but it appeared to indicate that to get the best results it was necessary to polish the surface of the spring after treatment, and that seemed to be a commercial impossibility; in many cases it was simply impossible to get at the spring to polish it after treatment. One must be content at least to sacrifice the reduction due to heat treatment, and the best that could be done would be to polish the material before heat treatment. Even with the best treatment the surface would not remain polished, and, as noted by the authors on p. 244, even that process would not enable the full resistance of the material to be utilised.

Dr. W. ROSENHAIN, F.R.S. (National Physical Laboratory), said he had been connected intimately with the work described in the paper in two ways, both as Chairman of the Panel of the Springs Research Committee for which the work was originally carried out, and also at the National Physical Laboratory. He felt that it was work which carried implications of great importance. Dr. Swinden had called attention to them in his remarks, and, personally, he desired to emphasise them possibly a little more. To realise the immense effect of the surface condition of steel on the fatigue strength was impossible until the figures had been repeated again and again over a wide range of steels. So large was the effect that, under existing conditions of spring manufacture—he was speaking of ordinary laminated springs for motor and transport vehicles of various kinds—he thought it was right to say that a slight difference in the character of the surface

was far more important than the type of steel, whether carbon or alloy, used for making the spring. It completely swamped the difference between a high-class alloy steel and the most ordinary steel that could be used for the purpose, and had a very striking and serious effect. The question was: What exactly did it mean? The attempted explanation given in the paper was necessarily a tentative one, because the investigation of the subject was one of very great difficulty. The view to which the authors appeared to lean—a view with which one could not quarrel at the time—was that it was mainly a question of surface decarburisation, rather than of cracking or defects produced on the surface as the result of heat treatment. He was not yet at liberty to refer to work which had been done since, both at the National Physical Laboratory and elsewhere, but it certainly had tended to shake his own conviction in regard to the supposed effect of the decarburised layer. Dr. Swinden had suggested that the polishing of the spring after it had been heat-treated was a commercial impossibility. It might be as regards cost, but it was not a physical impossibility in a laminated spring. One motor manufacturer producing a car which could certainly hardly be described as a commercial article had for a good many years been in the habit of doing it. He did not suggest such a thing could be done with a £100 car, but when it came to securing the full value of a material it might still be worth while. He had not by any means given up the hope that when at last the real reason and mechanism of surface defects had been discovered, if they were ever fortunate enough to do so, it would not be beyond the power of steelmakers and spring-makers so to handle the material as to minimise greatly those surface defects. As a matter of fact, something in that direction had already been attempted for a special purpose in connection with the production of wire for coil springs, and although complete success had not been obtained, very considerable advances had been shown to be feasible by methods which were not so heroic as grinding the surface after the spring was finished. The whole thing was a most important discovery in regard to the behaviour of materials when subjected to fatigue in the rough condition in which they were produced by rolling and heat treatment, without machining and polishing. It was a lesson which would have to be applied to many other things besides springs, although it made itself felt mainly under definite fatigue stresses. It had shown a state of affairs which was not suspected by the steelmakers, the spring-makers, and the users until that research was carried out. It afforded a useful example of the way in which a systematic investigation, begun solely for the purpose of determining which in a series of steels gave the best results, might lead, if properly pursued, to far-reaching discoveries, which at the time were not looked for at all.

Mr. S. A. MAIN (Sheffield) said that Dr. Rosenhain had pointed out one very clear feature of the results of the paper—namely, that,

generally speaking, there was not much choice between the various alloy steels. He thought that conclusion probably arose from the fact that the fatigue tests in the research had been of a rather limited character; that was, they had been made only with a zero mean stress. In a motor-car the springs started with a certain static load due to the dead weight, and the fluctuations which constituted the fatigue stresses were superimposed upon that static load. He ventured to think that if the steels were put through similar sets of tests in which there was a definite mean stress, by making the stress fluctuate between zero and a maximum, it was quite possible that there might then be a considerable differentiation between the properties of some of the alloy steels. Another point, also, was that, even if it were the case that the different steels were of an equal value in their resistance to fatigue, practical people must consider which steels were best from the manufacturing point of view—that was, which allowed a greater margin of freedom in heat treatment. His experience was that silico-manganese steel was a better steel, both in the rolling and in the heat treatment, than, say, chromium steel. That gave another point of choice between the steels. With regard to the toughness of the steel and the Izod value, it was mentioned on p. 241 that the significance of the Izod value of the steel was not quite known in connection with spring steel. He thought, however, that the characteristic which made for a high Izod figure might very well give an improved fatigue value when the stresses were applied, say, between zero and a maximum instead of with a zero mean stress. In the former case the stress tended to encroach into the plastic range. In connection with the authors' preliminary work on the difference between the fatigue value found in an actual spring and the ideal value as ascertained in the paper, it was, perhaps, not quite fair to go deeply into that subject, because the authors said they were only at the beginning of it, but there appeared to be an implication on p. 218 to which he wished to take exception, as he would not like to see it perpetuated. The statement was made there that "The immediate value of the work lies in showing that nearly all the steels investigated can be so heat-treated that they give a high resistance to bending fatigue, whereas the actual resistance of commercial heat-treated spring plates is low." He thought any reader might be excused for taking that to mean that there was something not quite right in the commercial heat treatment of spring steels. The heat treatment was very well carried out by reputable spring makers, both in regard to the selection of the temperature and quenching medium and the control of the operation. The treatment was carried out under pyrometric control within very close limits. On p. 242 the authors pointed out that there was something more than heat treatment in the question; for instance, the surface of the plate was not plain, but usually contained small irregularities of shape. He thought, therefore, the authors' introduction was not in accordance with their fuller views on the question so far as they had been formed.

He was quite in agreement with Dr. Rosenhain that, so far as matters had gone at present, the lower fatigue value of a spring leaf in service was not solely, nor probably mostly, due to decarburisation. A spring leaf as it came from the rolls and after heat treatment was not by any means a plain surface, and he thought it was rather those irregularities in the surface which affected the fatigue value of the spring than any question of a decarburised layer.

The AUTHORS replied that they were glad their work was accepted by members of the Institute who were in a position to speak with authority on spring steels. The systematic investigation of the general mechanical properties of the steels had been somewhat lengthy and laborious, but it had led, they thought, to results which were of importance, and they had little to add to the remarks which had been made by Dr. Swinden and Dr. Rosenhain. In reply to Mr. Main, the authors agreed that the statement referred to on p. 218 might be open to misinterpretation, and they hastened to say that it was not intended that any reflection should be cast on commercial methods of heat treatment. From their experiments, they were of the opinion that the fatigue resistance of any of the usual spring steels which had been quenched and tempered under normal conditions would be much lower when the surface had not been touched after heat treatment, than when the materials were in the polished condition. That appeared to be true irrespective of whether the heat treatment had been carried out on small pieces in the laboratory, or under commercial conditions in the works. Mr. Main had also referred to what were usually known as repeated bending fatigue stresses—that is, stresses which fluctuated between zero and a maximum. Until recently, bending fatigue tests of that type had received little attention from investigators, and no results were available at present from which any connection between the endurance fatigue limits of steels under repeated bending stresses and the Izod values could be deduced. In the opinion of the authors, however, Mr. Main's suggestion that "the characteristic which made for a high Izod figure might very well give an improved fatigue value when the stresses were applied between zero and a maximum" was not unreasonable.

This paper was also discussed at the Additional Meeting held at Sheffield on May 15, 1929.

Mr. G. STANFIELD (Sheffield) said that the authors' work, reported in the present and in a previous paper,¹ represented a very useful survey of the mechanical properties of all the usual types of spring steel after various heat treatments. There were two important aspects

¹ G. A. Hankins, D. Hanson, and G. W. Ford, *Journal of the Iron and Steel Institute*, 1926, No. II. p. 265.

of the work: one, which the authors had mainly endeavoured to investigate, was the determination of the intrinsic properties of the materials correctly heat-treated; the other aspect, which he thought, for Sheffield at any rate, was the more important one, was the consideration of what could be done to improve the performance of the finished articles—the final springs.

As the authors had said, the results tended to show that of all the spring steels available there was not really any one that specially stood out above the others on account of the superiority of the mechanical properties which could be obtained. The actual details of heat treatment, of course, varied with the particular composition selected, but with any composition there was a choice of conditions which could be obtained—either high tensile condition with very little ductility, or a lower tensile condition with quite a moderate degree of ductility—and that choice between the two extremes was available in any of the qualities with which the authors had experimented. It was, of course, for the spring manufacturers to decide, as they had in the main already decided, what condition was best to put into the actual springs.

There were several factors in the practical production of springs which did help to decide the relative merits of the steels; those factors related actually to the various manipulation troubles experienced in the production of springs. For instance, there was the warping effect on quenching; spring plates were usually quenched edge-on in the quenching medium, and very frequently the edge which went into the liquid first became convex to the rest of the plate. Cracking was also a very serious trouble. The skill of the spring hardener had to be brought to bear to guard against those troubles, and the choice of material for spring plates came back very largely to deciding which class of steel would not only give satisfactory mechanical properties, but would give them without interference from those various causes of such an order as to make the job an uneconomical one. From that point of view, the usual 0.5 to 0.7 per cent. carbon steel was a very satisfactory steel to deal with, except perhaps in the actual hardening. In the actual hardening, an oil-hardening steel did give less trouble, and that accounted, he believed, for the automobile spring makers' great preference for the silicon-manganese and chrome-vanadium steels.

The authors had rightly drawn attention to the importance of the surface. From the point of view of spring production, surface troubles were going to be a serious problem if that apparent inefficiency of the finished spring plate, to which there did not appear to be at present a satisfactory solution, were to be completely avoided. But, serious as that aspect of the matter was, he did think it was possible to exaggerate its importance. It was suggested that spring plates were being made with something less than 50 per cent. of the possible fatigue resistance. Now, fatigue resistance was not all that was wanted in a spring plate. In service, a spring had to withstand a considerable

number of serious deflections which imposed very high stresses; it also had to withstand a far greater number of very small deflections, and the spring maker had to cater for the small deflections and for the steady stress which was always on a spring plate due to the applied load, as well as for those stresses due to the occasional excessive deflections. He mentioned that because he thought it had been found that the effect of surface condition was a little less serious with a softer type of plate than with a hard type; he thought, however, that it would be dangerous to deduce from that fact that it would be wise to employ softer plates. The softer plates would not stand up to continuous stressing; the necessity for carrying a dead load without permanent set imposed quite severe constant stresses, and that must be kept in view all the time. The temptation to go in for a softer plate must, he thought, be resisted, at any rate for the time being.

Finally, he desired to ask the authors up to what limit would they be prepared to employ the ratio between fatigue limit and Brinell number which they had given.

Dr. W. H. HATFIELD (Member of Council) wished to emphasise the points that Mr. Stanfield had made. It should be noticed that when he spoke of the inefficiency of the finished spring he spoke of the apparent inefficiency. He (Dr. Hatfield) thought that in the present stage of knowledge it had better be left at that. If the suggested low value in the final spring were simply due to surface defects one would expect that efficiency to vary from 50 to 100 per cent., but it did not. If extraneous causes of disability, which they wrote down as surface defects, were introduced into the spring plates it was a fair deduction that they would introduce those influences to a different and varying degree. The authors themselves gave a percentage ratio of the efficiency of the material with the skin on in the final spring to its fatigue value in the polished specimen, of 50 per cent. He (Dr. Hatfield) would have placed it at about 60 per cent., which was practically the same figure for all practical purposes. The curious thing was that all who were doing similar work placed it at 50 to 60 per cent., and never so low as 5 or even 25 per cent. The point he wanted to make was that whilst that disability was of such a high order it was sought to put the whole disparity down to defects. They were always led to believe, as metallurgists, that the stress aspect was adequately cared for by the spring designer, who determined the stresses in the spring without referring back to the possibilities of the material. It was his conviction at the moment that there was something they did not understand, and he was sure they were not right in saying that because manufacturers of spring plates must necessarily, from the economic point of view, put that spring plate material into the surface, the disparity was in the main due to defects. As to the efficiency of the springs, there were many works in Sheffield with considerable experience of the response of springs under service con-

ditions, and it must be conceded that the efficiency of the springs produced was extremely high; in fact, the percentage of failures would be, he ventured to say, of such a low order as to exceed even the extraordinarily high efficiency which was normal with special technology. That in itself was another argument in support of his contention that the suggested inherent disability required further looking into.

The authors explained that the Brinell and tensile tests gave a fair indication of fatigue; they added that composition was secondary, always provided that the Brinell and tensile requirements were achieved. He (Dr. Hatfield) agreed, but he would point out to the authors that the necessary Brinell and tensile values for giving a required fatigue value were much more easily obtained when special elements were present. It was owing to that effect of the special elements, amongst which were manganese and silicon, in rendering the work easy and overcoming minor defects of manufacture, that the alloy steels were absolutely essential for highly stressed springs.

Professor C. H. DESCH, F.R.S. (Chairman), desired to ask the authors about what seemed to be an inconsistency in the latter part of the paper. It was stated that steel possessing the highest Izod value appeared to be the best to select for springs. It had been shown that the fatigue range was proportional to the tensile strength and the Brinell number—the better the fatigue range, the lower their value. One would suppose that the fatigue value was of much more importance than the Izod number, so that that inconsistency did not seem very easy to explain. He would suggest that a little too much stress had been placed on the Izod value. With reference to the surface, he thought he was right in saying that the effect of the outer skin on the fatigue limit in spring steel was first pointed out by Professor Lea in one of his earlier reports to the Springs Committee. How far that surface defect was due purely to decarburisation and how much to surface cracks had not yet been fully determined. It seemed to him that the surface cracks were of much more importance than the decarburised layer. In regard to the nature of that surface it would seem that some light might be thrown on it by heat-treatment experiments under quite different conditions, some in the ordinary furnaces such as were used for that work and some with special precautions to exclude decarburisation or chemical change. It would be interesting to determine whether those surface defects were due to chemical changes or were produced in the hardening. He knew that recently some curious inconsistencies had made their appearance in regard to that layer. Dr. Hatfield had remarked that springs on the whole were very satisfactory, but they could take it that if that surface defect could in any way be overcome they could get a considerable increase in the efficiency of the spring, and that would presumably mean a reduction in the amount of metal required for a given purpose.

Dr. HANKINS, in reply, thanked the various speakers for their remarks, and hoped that the general investigation of the mechanical properties on polished specimens could be regarded as a standard work on spring steels. In reply to Mr. Stanfield, and in view of the trouble which he (Dr. Hankins) and Miss Ford had experienced with hardening cracks in their 0.6 per cent. carbon steel, it was some consolation to know that even in Sheffield difficulty was experienced in avoiding those cracks in some spring steels when quenched in water. As Mr. Stanfield had remarked, the skill of the worker was of considerable importance in guarding against that trouble. He agreed that the surface condition was not so important in a relatively soft spring steel as in a hard spring steel. The softer spring gave undue "settling down" in use, which was objectionable, whilst the harder spring was more liable to be influenced by surface conditions lowering the fatigue resistance. He thought, however, that in some cases, perhaps, a satisfactory mean had not yet been obtained in that matter, and that some springs were so hard that the advantage of a high elastic range was more than outweighed by the extra liability to fatigue failure due to surface defects. The approximate ratio of the rotating cantilever endurance fatigue limit to the tensile strength or Brinell number appeared to hold up to 500 Brinell number, but it should be understood that it was not a simple matter to obtain satisfactory determinations of fatigue limits on such hard steels. Great care was necessary in the preparation of the test specimens and in the practical details of the tests, and failures due to extraneous causes, such as lack of uniformity in the material or vibrations in the testing machine, always tended to give values of the fatigue limit which were lower than the correct value.

He could hardly agree with Dr. Hatfield that 50 per cent. was usually given as the percentage ratio of the efficiency of an unpolished spring to the polished material. Thus, results were given in the paper (pp. 243 and 244) of tests on 0.6 per cent. carbon steel springs and on the actual material. The complete springs gave an endurance limit of 0 to 20 tons per sq. in., whereas the value for the material was ± 38 , or a range of 76 per tons per sq. in. It was hardly necessary to enter into a discussion of the relation between repeated stresses and reversed stresses, but in this case it seemed quite clear that the efficiency of the complete spring was much less than 50 per cent. The main surface conditions which affected the fatigue resistance appeared to be decarburisation, stress concentration due to irregularities, internal stresses set up by quenching, and surface cracks, possibly of a sub-microscopic nature, but other unknown factors might also be present.

Dr. HATFIELD interposed that he wanted to emphasise that the fatigue test was carried out on the machine-ground test-piece in a fatigue testing machine, and that value was compared with that obtained on the finished spring. Accordingly, there arose the question

of calculating the stresses, and the question whether the stress in the spring which was established were the correct one.

Dr. HANKINS (*continuing*) said he was satisfied that the figure of 0 to 20 tons per sq. in. which he had quoted was correct, but he would also refer Dr. Hatfield to Table XIII.; those tests were carried out under identical conditions in the two cases, and there was no doubt in his mind that the lower values on the unpolished specimens were due to surface conditions brought about by the heat treatments.

The CHAIRMAN (Professor C. H. Desch, F.R.S.), interposing, remarked that in the work which Professor Lea was doing on coil springs the two sets of springs were tested in the same way; one had the surface removed from the wire, and the other had not. He believed that the results had been sent to the Springs Committee, but he had not got the figures.

Dr. HANKINS (*continuing*) stated that his experience supported Dr. Hatfield's contention that alloy steels should be used for highly stressed springs. He had already remarked that considerable care in preparation and heat treatment was necessary in order to obtain the high values of the fatigue limits recorded in the paper, but the care required was not nearly so great with alloy steels as with carbon steels.

With reference to the point raised by Professor Desch in regard to Izod values, he (Dr. Hankins) suggested that if it were possible to use a perfectly polished steel spring under ideal conditions, then the Izod value of the material would be unimportant, and the safe stresses on the spring would depend on its intrinsic fatigue limit alone. When manufacturing imperfections in the form of unpolished surfaces were present, however, the suggestion was made that some importance might be attached to the Izod figure of a spring steel. He was pleased to have Professor Desch's opinion that experiments in which special precautions were taken to exclude decarburisation or chemical change might be of value, and he was glad to say that work on those lines had already been initiated.

A NEW METHOD FOR THE PRODUCTION OF SOUND STEEL.¹

BY THE HON. SIR CHARLES PARSONS, O.M., K.C.B., F.R.S.,

AND

H. M. DUNCAN, B.Sc. (NEWCASTLE-UPON-TYNE).

INTRODUCTION.

IN 1924 a Committee of the Iron and Steel Institute was formed for the purpose of studying the problems of inclusions in steel and of the heterogeneity of steel ingots. They have published two Reports on the heterogeneity of steel ingots. The first, published in 1926,² dealt with steel ingots of the "killed" variety produced under good conditions; the second, published in 1928,³ dealt with steel other than killed, and also with certain alloy steels.

A large number of ingots, ranging from 15 cwt. to 172 tons in weight, were examined by analysing, sulphur-printing, and macro-etching longitudinal sections taken along the axis. These Reports contain the most complete information published of the heterogeneity present in steel ingots, and the Committee are to be congratulated on the frank way in which they presented this information. In the present paper the authors will not deal with the results disclosed, except to express the opinion that the pronounced segregation and axial weakness found in every ingot examined was not generally known to engineers.

In the First Report⁴ the Committee stated in their reply to the discussion: "They would point out . . . that the Report was *not* put forward as propaganda for inducing engineers to modify their apparently unreasonable requirements. The Report is simply a record of an investigation undertaken to determine the nature and extent of heterogeneity which is prevalent in steel ingots produced under good conditions. The facts disclosed are worthy of very serious consideration by the engineering world,

¹ Received March 22, 1929.

² *Journal of the Iron and Steel Institute*, 1926, No. I. pp. 39-151.

³ *Ibid.*, 1928, No. I. pp. 401-547.

⁴ *Loc. cit.*, p. 174.

and the Committee feel that engineers will be wise to bear them in mind." This statement, coming from such an authoritative source, must be seriously considered by all engineers.

THE NEW METHOD OF CASTING.

The authors' method of overcoming segregation and axial unsoundness is based on the principle that the freezing of the ingot should proceed from the bottom upwards, the isothermals being substantially parallel to the bottom of the ingot.

A patent, No. 278032, was granted to the authors for a process of casting steel ingots comprising the pouring of the molten metal into a mould having its longitudinal dimensions greater than its vertical, thick refractory materials covering the sides of the mould and a bottom chill of large dimensions, preferably of metal, preheating the mould to a high temperature of the order of molten steel before pouring the metal therein, and continuously supplying heat to the upper surface of the molten metal after casting, so that the upper layer is the last to solidify.

Fig. 1 represents a section of an ingot and mould. The mould consists of a strong sheet steel casing (*a*), slightly conical in form as shown and reinforced by heavy angles (*b*) at the top and bottom. The casing is lined with shaped firebrick quorls (*d*) closely fitted together and to the outer casing, and is preferably provided with lifting eyes (*c*) riveted to the sides.

The cover (*e*) is likewise made of suitably shaped firebrick quorls fitted together and into a massive steel angle ring (*f*), which retains them. The cover (*e*) may be lifted by the eyes (*g*) riveted to the ring (*f*).

In the cover one or more suitable holes (*h*) are provided for the insertion of gas or oil burners (*j*), and also one or more suitable vent-holes (*k*) to allow the hot gases to escape. These burners are used for applying heat to the surface of the metal after pouring, in order to keep the top layer molten until the last, while the mould is preheated by placing it, with its cover in place, on the top of an adjoining firebrick table containing suitable gas or oil burners delivering flame upwards. If desired, the burners (*j*) may be used for preheating the mould. The cover is also provided with a hole (*l*) for use when pouring.

The chill block (*m*) may be of cast iron or steel formed of one or more pieces fitted together; it is preferably protected on its upper surface against the wash of the molten steel by a thin steel plate (*n*), which is easily renewable.

A circular ingot, height 45 in., diam. 70 in., and weight $20\frac{1}{2}$ tons, was cast by the new method. Fig. 5 (Plate XXVI.) is a sulphur

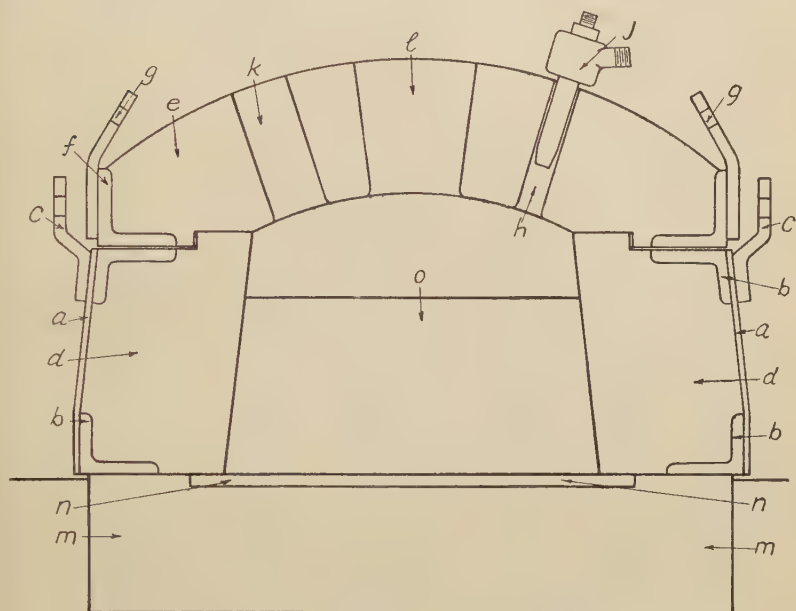


FIG. 1.—Section of an Ingot and Mould.

print of a longitudinal section of the ingot at its central axis; the white bands are areas of lower carbon and phosphorus content. Fig. 6 (Plate XXVII.) shows the macrostructure; it will be noted that there is no trace of V-segregate or axial weakness, and the main segregate is only noticeable at the top, which would be discarded. Fig. 2 gives the chemical composition, and attention is drawn to the uniformity and to the absence of serious segregation.

The mechanical properties of the ingot are shown in Table I. and in Fig. 3; the positions from which the test-pieces were taken are indicated in Fig. 7 (Plate XXVIII.). Further results are shown in Fig. 9 (Plate XXIX.), to which Fig. 9A (p. 265) is a key.

TABLE I.—*Mechanical Tests from Central Slice.*

Piece.	Tensile Tests.				Izod Test. Ft.-lb. 120-ft.-lb. Machine.	
	Yield. Tons per sq. in.	Break. Tons per sq. in.	Elongation. %	Contraction. %	1.	2. 3.
1L	18.5	26.5	1.0	Nil	1.5	2.5 2.3
2T	19.0	21.0	Nil	Nil	1.8	1.8 2.0
3L	13.5	31.5	15.0	20.5	5.0	5.1 5.0
4T	14.0	31.7	12.5	14.0	4.0	5.0 5.0
5L	12.0	29.8	17.0	23.0	5.5	8.5 6.0
6T	12.0	28.5	14.0	18.0	6.7	5.5 5.2
7L	12.0	29.5	17.5	21.0	5.1	6.8 10.3
8T	11.0	28.3	13.5	18.0	9.0	6.0 7.5
9	11.0	25.7	12.0	15.5	...	...
10T	13.0	29.5	32.5	45.5	6.5	4.5 8.0
11L	15.0	29.8	25.0	38.5	10.5	8.5 5.2

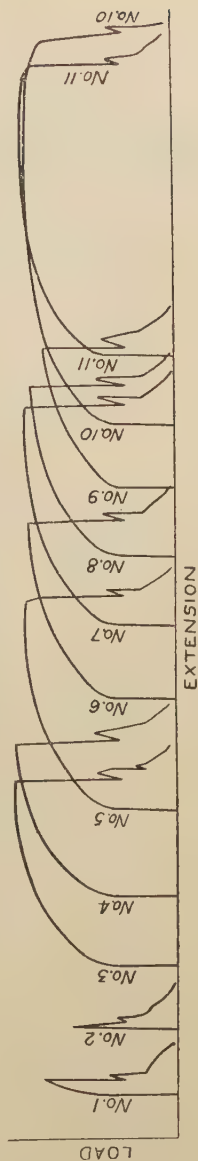
 L = longitudinal; T = transverse.

FIG. 3.—Graphs of the Mechanical Properties.

A more detailed examination was made of two sections cut from the positions shown in Fig. 4. The centre section was

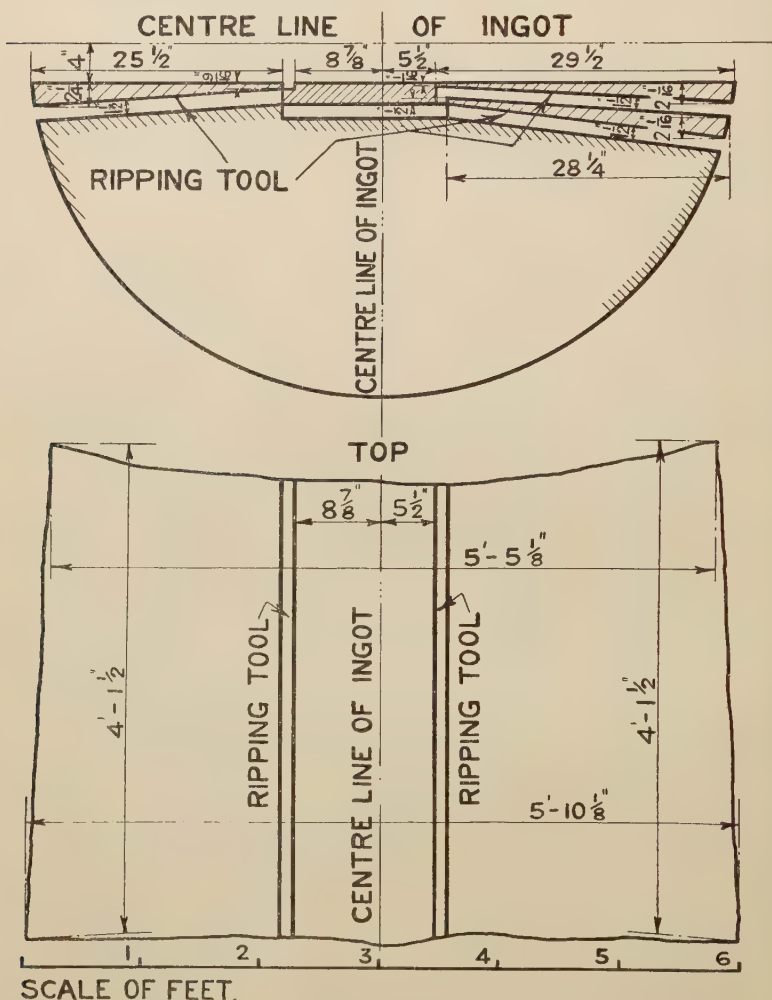


FIG. 4.—A Section of the 20-ton Ingot, showing the position of the central section (Figs. 7 and 8, Plate XXVIII.), and the adjoining section (Fig. 9, Plate XXIX.).

etched, first with 5 per cent. alcoholic nitric acid, and then Heyn's reagent. The etching picture showed long narrow grains, stream-

ing with slight inward curvature to a horizontal line just below the tails of the top segregate.

The surface was next etched with Humfrey's reagent, the acidity being increased from 0 to 4 per cent. until the etch was deep enough for contact printing. Fig. 8 (Plate XXVIII.) is a reproduction from one of them to a scale of about one-seventh.

Some features of the structure, from the bottom up, are :

- (a) A fine equiaxed layer, about 1 in. thick.
- (b) A columnar layer, 5 in. deep, crossed by several very narrow transverse markings. These markings were surrounded by shorter grains, which appeared darker in the print.
- (c) General equiaxed graining from the columnar zone upwards, except for one white band of long and almost vertical dendrites.
- (d) Bands of longish dendrites of no special orientation occurring within the equiaxed zone up to the top quarter.
- (e) Fine and uniform graining of the top quarter, with the exception of the top segregated zone, which is dendritic.

The transverse markings appear roughly to follow the isothermals. The tensile test, No. 9, Table I., taken across one of these markings, revealed a definite flaw and reduction in strength. Micro-examination of section *F*, Fig. 7, containing the plainest of these markings, showed an almost continuous line of inclusions in a ferrite band. This is also illustrated in Fig. 16 (Plate XXXI.), and at *Y* and *Z* in Fig. 18 (Plate XXXII.).

As all steel makers and steel users know, non-metallic inclusions are among the most harmful defects which occur in steel, and particularly if they occur in definite bands, as they have done in this case. All steel makers know that when a stream of liquid steel strikes the cold bottom of a mould and spreads over its surface, the fluid metal is considerably cooled, and may even become solid. As the mould at this stage is full of air, oxidation takes place; the oxide is liquefied by further additions of fluid metal, and, according to generally accepted ideas, it should float to the surface, but, unfortunately, owing to the downward pressure of the stream of metal, much of this scum is retained in the bottom portion of the ingot. It is generally found in practice that as the

area of the ingot is increased, the amount of non-metallic inclusions in the product is usually greater. In order to minimise this defect, it is necessary to flood the mould bottom as quickly as possible.

In the case of the authors' ingot, it should be borne in mind that the area is very great—6 ft. in diam.—and, further, the bottom is composed of plates 6 ft. deep, in order to induce very rapid cooling. As the nozzle was only $1\frac{1}{2}$ in. in diam., the flooding of the bottom was slow, and consequently oxidation would occur, with the formation of scum.

In the authors' opinion these transverse defects can be entirely prevented by a proper teeming speed, using more or larger nozzles, and in confirmation of this a 3-ton ingot, 3 ft. in diam., cast with a nozzle $1\frac{1}{8}$ in. in diam., was found to be entirely free from these defects.

MICROSTRUCTURE.

Microsections were taken from the positions *A, B, C, D, E*, and *F*, in Fig. 7. Inclusions of various types were visible in the unetched specimens. The more numerous were very small, and occurred mostly in lines. There were, however, a few large isolated inclusions showing a duplex structure.

Micrographs of representative fields are given in Figs. 10 to 15 (Plates XXX. and XXXI.) ; Figs. 16 and 17 are taken from specimen *F*. All specimens were etched with nitric acid. Figs. 10, 11, and 12, from the segregated zone, show, respectively, inclusions in the ferrite, rather high carbon, and a phosphorus-rich area with many inclusions. Fig. 13 shows a coarser structure with more ferrite than Fig. 11. Fig. 14 is similar to Fig. 13. Fig. 15, from the chilled zone, shows more ferrite with less marked patterning, and definitely selective etching of the ferrite grains.

Figs. 16 and 17, from specimen *F*, show numerous small and a few large isolated inclusions in a ferrite band.

Examination of Section adjoining Central Section.—This section was sulphur printed, as shown in Fig. 9 (Plate XXIX.). Fig. 18 (Plate XXXII.) shows the structure revealed by ammonium copper chloride solution, etched first by a 12 per cent. neutral solution, then with acid added up to 5 per cent.

Fig. 19 (Plate XXXIII.) shows the result of etching with 5 per cent. nitric acid solution. This method of etching is more drastic

than the copper ammonium chloride, and consequently destroys the outline of the primary crystallisation. This only shows the secondary crystallisation—that is, the structure which is formed within the primary network. There is a line of fine crystals at the extreme bottom end of the ingot, from which grow columnar crystals for a distance of about 6 in. ; above this is an area of indeterminate structure, then an outline of crystals, and towards the outside a very marked crystalline structure.

Figs. 20 to 25 (Plate XXXIV.) are micrographs taken approximately half-way between the centre and outside of the ingot, as shown in Fig. 9 (Plate XXIX.). The numbers indicate the approximate distance of the specimens from the bottom end of the ingot. Figs. 26 to 30 (Plate XXXV.) are micrographs of the same areas as are shown in Figs. 20 to 25, after annealing in blocks at 980° C.

MECHANICAL TESTS.

Mechanical tests were also taken from this section, and, in order to show their position in relation to the segregates, the results are marked on the sulphur print, Fig. 9 (Plate XXIX.) (see key diagram, Fig. 9A). In addition, the position of the microsections Nos. 2, 15, 17, 30, 40, and 45 (Figs. 20 to 30, Plates XXXIV. and XXXV.), are also entered on the sulphur print, Fig. 9.

The mechanical tests were taken (1) as cast, and (2) as cast, then heated to 980° C. and cooled in the furnace. The latter series have the letter *A* affixed to each test result.

The ingot can be forged in the ordinary way under a vertical press by casting a head or stalk on the top of the ingot after it has just set, thus enabling a porter bar to be used. This has been done with an ingot weighing 20 tons, and the ingot, 72 in. in diam., forged to a bloom 40 in. in diam. in one heat.

SEGREGATION.

In considering the heterogeneity of a steel ingot as disclosed by analysis, it must be remembered that such analyses only give the average composition of the material drilled from a $\frac{3}{8}$ -in. or $\frac{1}{2}$ -in. hole, and are not a satisfactory guide to the intensity of the

segregation and its evil effect, as the drillings always contain purer metal which dilutes the samples.

Judged by the results obtained by analysis alone, there would not appear to be much difference between the amount of segrega-

Mechanical Tests on Pieces taken from the Positions shown in Figs. 9 and 9A.

Piece.	Ultimate Strength. Tons per sq. in.	Elongation on 2 in. %	Contraction of Area. %	Approx. Yield Point. Tons per sq. in.	Izod Value. Mean. Ft.-lb.
TL	32.6	13.0	21.6	...	6
TLA	33.0	12.0	15.2	18	4
TX	30.5	12.0	18.4	...	5
TXA	32.2	22.5	36.4	16	7
CL	29.0	18.0	23.2	...	6
CLA	30.3	27.0	50.0	15	8
CXSA	27.6	10.0	15.2	15	...
CX	28.3	21.0	27.6	...	6
CXA	30.2	27.0	44.8	13	8
BL	28.5	26.5	47.2	...	8
BLA	30.4	26.5	47.2	14	9
BX	28.8	22.0	47.2	...	6
BXA	31.4	26.5	46.0	15	8

tion in the authors' ingot and that in an ingot cast by the best ordinary method, but if the sulphur prints and macrographs from these ingots are examined, the difference is seen to be very marked in favour of the new method. Further, when the great loss of ductility across the segregated areas in the ordinary ingot, as shown in Table II., is borne in mind, it is felt that sulphur printing gives a truer indication of the harmful segregates than analysis.

The left half of Table II. gives the results of mechanical tests taken radially across a segregated zone from a forging 57 in. in diam. cast in the ordinary way ; the right half of Table II. gives the mechanical tests of the material nearer the outside of the same forging.

Attention is directed to the very serious loss in ductility met with in the segregated zone ; as these zones run in a longitudinal direction, forgings and guns exposed to centrifugal or bursting stresses are considerably handicapped.



FIG. 5.—Sulphur print of a longitudinal section of the 20-ton ingot at its central axis.



FIG. 6.—Macrostructure of a longitudinal section of the 20-ton ingot at its central axis.

(Top of ingot.)

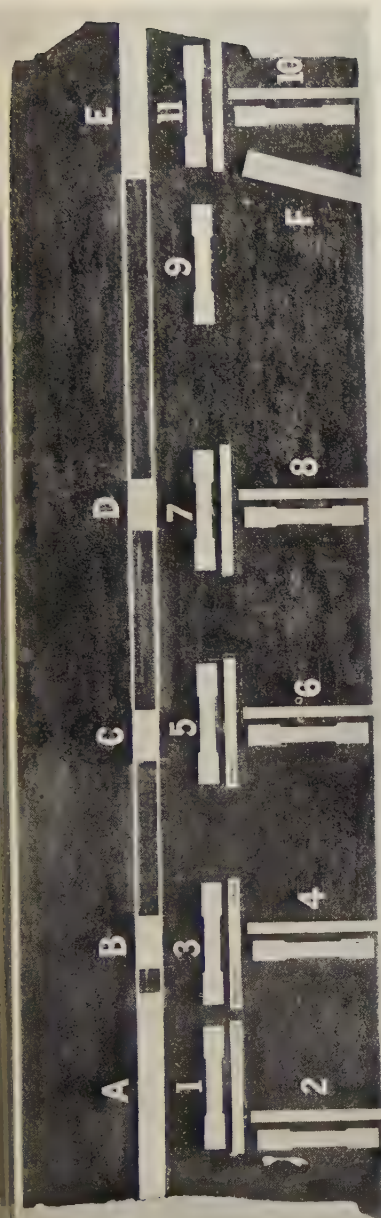


FIG. 7.—The positions of test-pieces and microsections taken from the central slice of the 20-ton ingot.

(Top of ingot.)



FIG. 8.—Contact print from the central section of the 20-ton ingot.

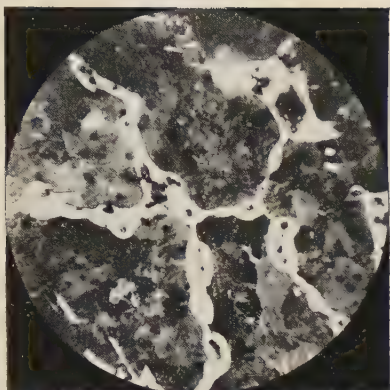


FIG. 10.—The segregated zone, position *A* in Fig. 7 (Plate XXVIII.), showing inclusions in the ferrite. $\times 50$.

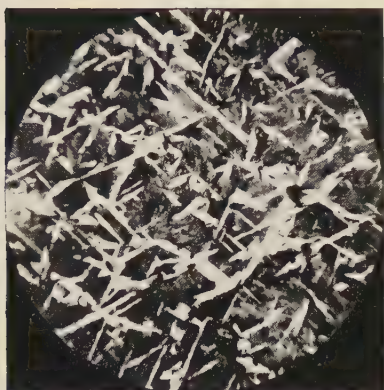


FIG. 11.—The segregated zone, position *A* in Fig. 7 (Plate XXVIII.), showing rather high carbon. $\times 50$.

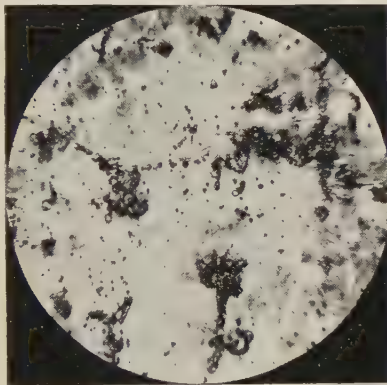


FIG. 12.—The segregated zone, position *A* in Fig. 7 (Plate XXVIII.), showing a phosphorus-rich area with many inclusions. $\times 50$.



FIG. 13.—Position *C* in Fig. 7 (Plate XXVIII.), showing a coarser structure with more ferrite than Fig. 11. $\times 50$.

(The above micrographs were reduced in reproduction to two-thirds.)



FIG. 14.—Position *D* in Fig. 7 (Plate XXVIII.); similar to Fig. 13. $\times 50$.

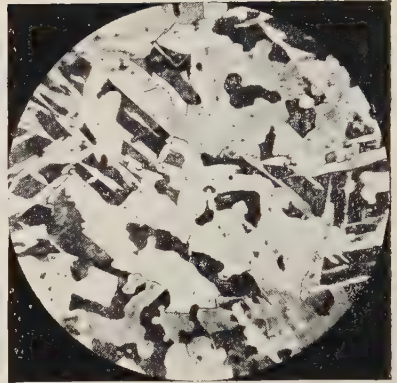


FIG. 15.—Position *E* in Fig. 7 (Plate XXVIII.); the chilled zone. $\times 50$.



FIG. 16. $\times 50$.

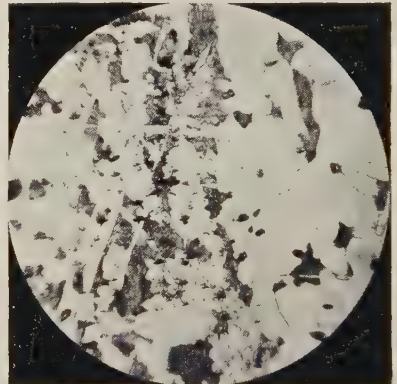


FIG. 17. $\times 50$.

FIGS. 16 and 17.—Position *F* in Fig. 7 (Plate XXVIII.), showing numerous small and a few large inclusions in a ferrite band.

(The above micrographs were reduced in reproduction to two-thirds.)



Fig. 18.—Macrostructure of a section adjoining a central slice from the 20-ton ingot, showing transverse lines Y and Z.



Y

N

FIG. 19.—Same section as Fig. 18 (Plate XXXII.), etched with 5 per cent. nitric acid, showing secondary crystallisation.

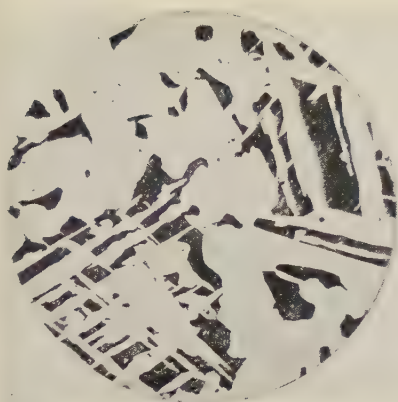


FIG. 20.—Specimen No. 2. Etched with picric acid. $\times 60$.

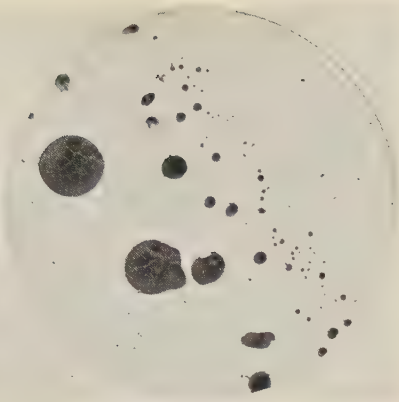


FIG. 21.—Specimen No. 15. Unetched. $\times 100$.

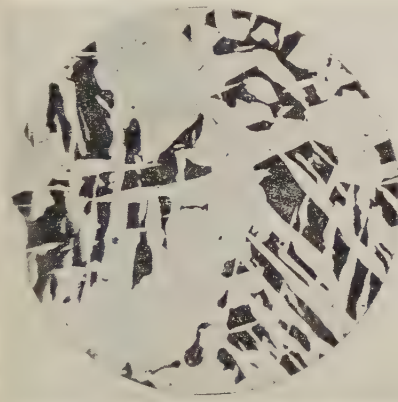


FIG. 22.—Specimen No. 17. Etched with picric acid. $\times 60$.

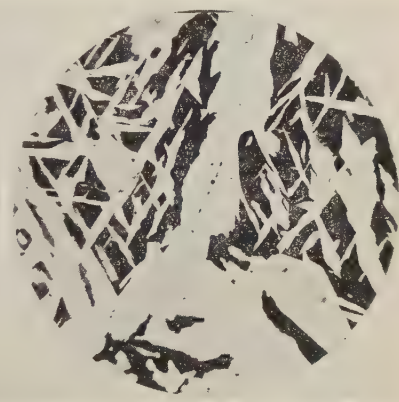


FIG. 23.—Specimen No. 30. Etched with nitric acid. $\times 60$.

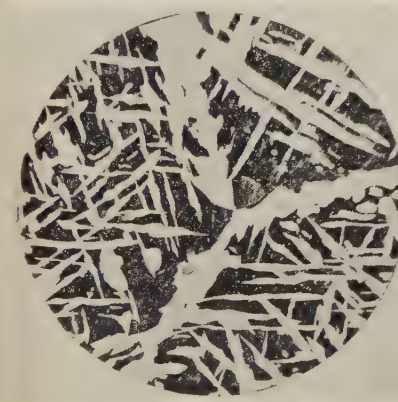


FIG. 24.—Specimen No. 40. Etched with picric acid. $\times 60$.



FIG. 25.—Specimen No. 45. Etched with picric acid. $\times 60$.

FIGS. 20 to 25.—Micrographs taken approximately half-way between the centre and outside of the ingot as shown in Fig. 9 (Plate XXIX.). The numbers indicate approximately the distance in inches of the specimen from the bottom end of the ingot. (The above micrographs were reduced in reproduction to two-thirds.)



FIG. 26.—Specimen No. 2A. Etched with picric acid. $\times 60$.



FIG. 27.—Specimen No. 17A. Etched with picric acid. $\times 60$.



FIG. 28.—Specimen No. 30A. Etched with picric acid. $\times 60$.

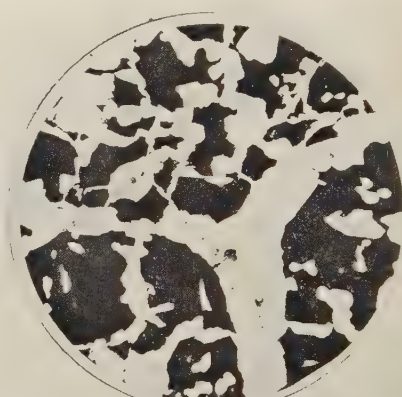


FIG. 29.—Specimen No. 40A. Etched with picric acid. $\times 60$.



FIG. 30.—Specimen No. 45A. Etched with picric acid. $\times 60$.

Figs. 26 to 30.—Micrographs of the areas shown in Figs. 20 to 25 (Plate XXXIV.), after annealing in blocks at 980°C .

(The above micrographs were reduced in reproduction to two-thirds.)

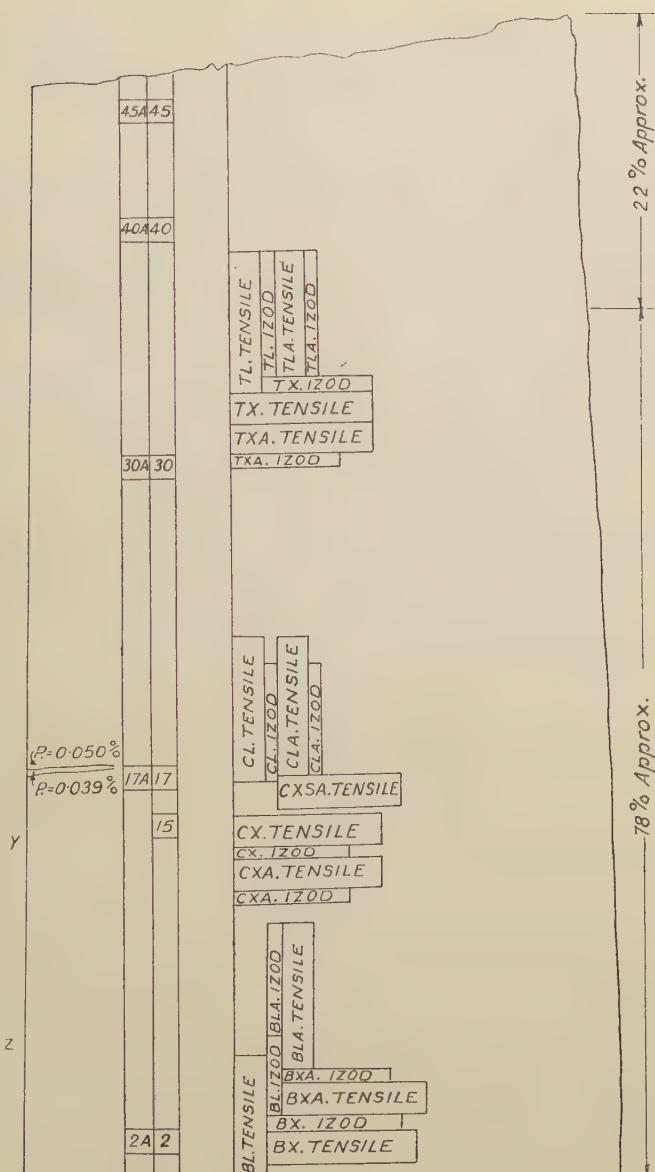


FIG. 9A.—Key to Fig. 9 (Plate XXIX.).

[The mechanical tests are recorded in the table on p. 264.]

Woodvine and Roberts,¹ in a paper on "The Influence of Segregation on the Corrosion of Boiler Tubes and Superheaters," stated (*loc. cit.*, p. 221): "Where it has been possible to get positive evidence from service failures the trouble could usually be traced to segregated steel."

The Heterogeneity Committee have pointed out that segregation increases with the size of the ingot, and as the stresses due

TABLE II.—*Radial Test-Pieces Cut from a Transverse Section of a Large Forging, 57 in. in diameter, made in the Ordinary Way.*

<i>Across the Segregate.</i>				<i>Near the Outside.</i>			
Yield Point. Tons per sq. in.	Ultimate Strength. Tons per sq. in.	Elongation on 2 in. %	Reduction of Area. %	Yield Point. Tons per sq. in.	Ultimate Strength. Tons per sq. in.	Elongation on 2 in. %	Reduction of Area. %
18.0	21.92	2.0	4.9	17.8	34.0	24.0	33.5
18.6	23.24	3.5 O.M.H.	4.9	18.8	34.68	23.0	24.5
18.8 X	...	3.0 O.G.L.	...	18.6	35.6	20.0	24.5
18.2	31.8	7.0	11.7	18.0	35.52	21.5	33.5
18.8	31.2	6.0 O.G.L.	11.7	18.8	35.2	24.0 O.M.H.	24.5
18.6	31.4	8.0 O.M.H.	11.7	17.8	34.56	30.5	47.2
18.4	29.48	5.0	8.4	19.2	34.0	21.5	30.6
18.8	26.28	4.5	8.4	17.0	33.96	24.0	33.5
18.5	27.9	4.9	8.8	18.2	34.6	23.6	31.5

O.M.H. = outside middle half.

O.G.L. = outside gauge length.

X = broke in radius.

to heating or cooling also increase in proportion to the mass, the manufacture of large forgings free from internal fissures becomes increasingly difficult, and the utmost care must be exercised to produce a sound forging; in designing, a large factor of safety must be allowed on account of the segregated areas. Since modern electrical rotors are becoming larger and larger, and there is no satisfactory alternative to a solid forging, it becomes increasingly important that some method should be adopted whereby segregation and axial weakness may be diminished or avoided altogether.

Probably everybody will agree that steel free from segregation and axial weakness is to be preferred for every purpose, provided it can be obtained at a reasonable cost, and the authors think that this can be secured by their process.

¹ *Journal of the Iron and Steel Institute*, 1926, No. I. pp. 219-222.

DISCUSSION.

Mr. DUNCAN, in introducing the paper, presented the following additional information : It will be noticed in Fig. 1, a diagram of the mould and cover used for casting the first 20-ton ingot by the new method, that the holes in the cover for the insertion of the oil burners were directed towards the centre of the mould, thereby concentrating the heat on the centre of the top surface of the solidifying ingot, thus preventing the segregates from rising to the top at the sides of the mould, as the sides towards the top froze before the central portion.

This was remedied, and a second 20-ton ingot was cast in a mould having the burners spaced round the walls of the mould, thereby concentrating the heat on the periphery and letting the centre take care of itself. An illustration of this mould and cover is shown in Fig. A (p. 268). Oil burners were not used to keep the top of the second ingot hot after casting, this being accomplished by placing coke on top of the molten steel and layer of slag, and blowing a gentle stream of air through the openings in the sides of the mould. When the ingot had completely solidified, a box, 2 ft. in diam. by 3 ft. high, was placed on top, and filled with molten steel to enable the ingot to be manipulated in the forge by placing a porter bar over the stalk or head thus formed. By this means the ingot was forged into a bloom 40 in. in diam. in one heat. After annealing it was cut into cheeses, and sulphur prints, Figs. C to H (Plate XXXVa.), were taken from the face of each cheese. Fig. B (p. 269) is a sketch showing the ingot after blooming, the positions of the cheeses, and the mechanical tests obtained from the centres of these cheeses after they had been forged into discs of the dimensions shown.

The authors wished to draw attention to the uniformity of the test figures and to the very excellent results which were obtained in the thickness or "C" direction (see Fig. B), as tests taken in this direction from ingots cast in the ordinary way generally show much lower ductility.

Dr. W. H. HATFIELD (Member of Council), speaking as Chairman of the Committee on the Heterogeneity of Steel Ingots, said that the paper had been read by the members with special interest. It had been gratifying to find that the publication of the researches of their Committee had led Sir Charles Parsons and Mr. Duncan to perform such a bold experiment. Some time ago the Committee's attention had been drawn to their work, and opportunity had been given to them to study the actual 20-ton ingot. Of such interest did they find the experiment, that they suggested that the Institute should invite Sir Charles to present this paper.

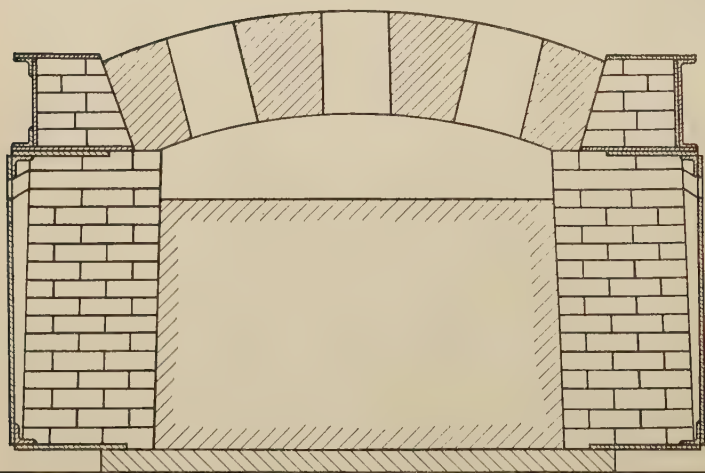
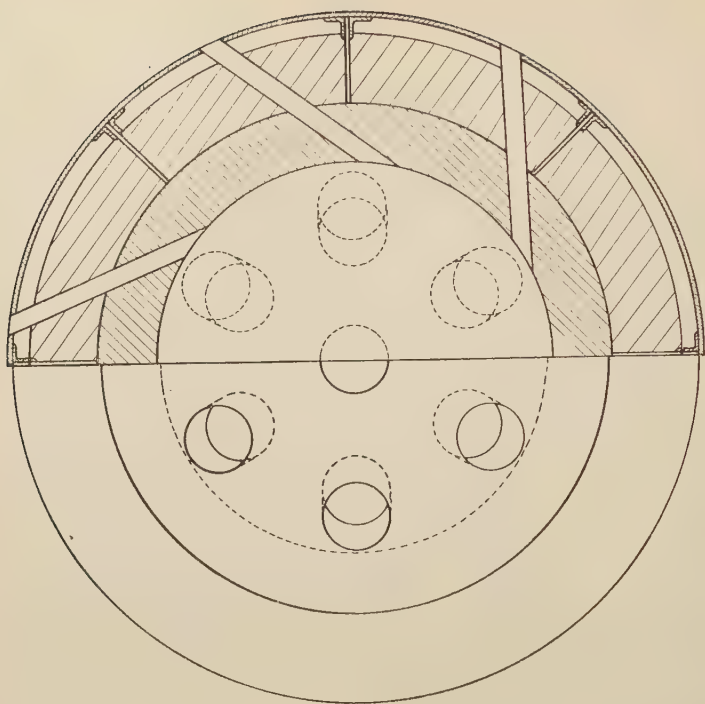
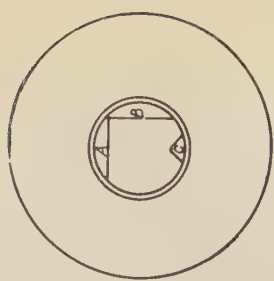
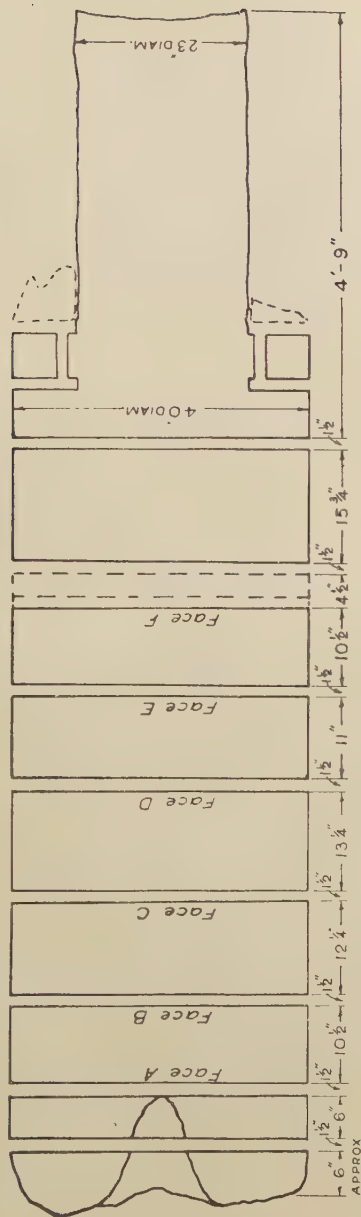


FIG. A.—The Second Mould used for Casting a 20-ton Steel Ingot by the Authors' Method.



Disc number	501	502	503	498	500	Charge Analysis.
Forged size	57" diam. \times 4 1/8"	59" diam. \times 4 1/8"	59" diam. \times 5 1/8"	51 1/2" diam. \times 6"	57" diam. \times 4 3/8"	Si. % Mn. % C. % P. % S. %
Position	A	B	O	A	B	O
Limit of proportionality, Tons per sq. in.	10.4	12.0	...	12.0	13.2	...
Yield point, Tons per sq. in.	16.5	16.5	18.0	17.5	18.0	18.0
Ultimate strength, Tons per sq. in.	31.4	32.0	31.2	31.7	31.4	30.8
Elongation on 2 in. %	31.5	31.5	26.5	30.0	31.5	27.5
Contraction of area, %	53.1	56.0	47.2	50.0	53.1	47.2
Bend	180°	180°	...	180°	180°	...
Heat Treatment.	620° C. to 630° C. — 5 hr. — Air-cooled	900° C. — Uniform — Air-cooled	560° C. — 1 hr. — Air-cooled	620° C. to 630° C. — 5 hr. — Air-cooled	900° C. — Uniform — Air-cooled	560° C. — 1 hr. — Air-cooled
Percentage of Total Weight.						
	Below Face A	Below Face A	Below Face A	Below Face A	Below Face A	Below Face A
	9 1/2 %	9 1/2 %	9 1/2 %	9 1/2 %	9 1/2 %	9 1/2 %
	46 1/2 %	46 1/2 %	46 1/2 %	46 1/2 %	46 1/2 %	46 1/2 %
	41 1/2 %	41 1/2 %	41 1/2 %	41 1/2 %	41 1/2 %	41 1/2 %
	W.F., W.F.	W.F., W.F.	W.F., W.F.	W.F., W.F.	W.F., W.F.	W.F., W.F.

Fig. B.—Bloom from the Second Ingot (20 tons).

Sketch Indicating Position of Tests.

Some members still thought the equiaxed crystal structure to be the most desirable, but many of them agreed that the authors' conception had been idealistic—that was, to obtain in practice uni-directional freezing from the bottom upwards, without the introduction of other disabilities. If that could be obtained, there was no doubt that, from the latter point of view, a great advance would have been achieved. It was therefore of interest to consider in detail the degree to which the authors' process permitted the attainment of their ideals. Fig. 6 rather indicated that that had not been fully achieved, owing to disturbances caused by freezing from the top downwards and also from the walls of the mould, the effect in the latter case increasing towards the top of the ingot. That was due to practical difficulties of temperature regulation, and had a serious effect in leaving segregates in such a position as to render necessary a quite substantial discard (see Fig. 5, Plate XXVI.).

Heating of the mould walls could not prevent the effect of differential freezing, as was shown, for example, by comparing the carbon contents at the positions C3, C6, and O4 (Fig. 2), which were respectively 0.29, 0.20, and 0.17 per cent., although theoretically it might have been anticipated that the segregate would largely have found its position as a top layer of the ingot. The practical effect, also, of the hot walls must surely be that the consequent delaying of the freezing would lead to the production of a very coarse structure and increased size of the non-metallic inclusions.

The Committee were desirous of more information concerning the light bands in Fig. 5, which occurred roughly parallel to the base. Had the authors any views as to the cause of those zones of apparently dissimilar composition? One important fact not mentioned in the paper was that when sectioning this ingot along the axis, a shell of steel of appreciable thickness split off one of the sectioned faces. Having in mind that the cylindrical form of ingot adopted was conducive to high internal stress, that might possibly be the explanation. The Committee considered that phase of the matter as meriting serious discussion.

There were two further points of a practical character which might be mentioned. In the last paragraph of p. 261, consideration was given to the initial liquid steel entering the mould, but the Committee would remind the authors that in practice a "well" was provided at the bottom of big ingots to minimise the effect mentioned. The other point concerned the suggestion of casting a stalk on the authors' type of ingot for forging purposes after the ingot had become solid. That, the Committee believed, would hardly serve the intended purpose, since it would most probably break off at the root during the forging process.

Turning to more general matters, exception was taken to the shape of the ingot on the grounds that it did not conform with practical experience, which had shown that the depth in the chill should be about

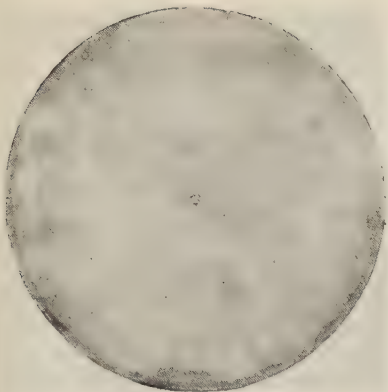


FIG. C.—Sulphur print from face A.
(See Fig. B.)

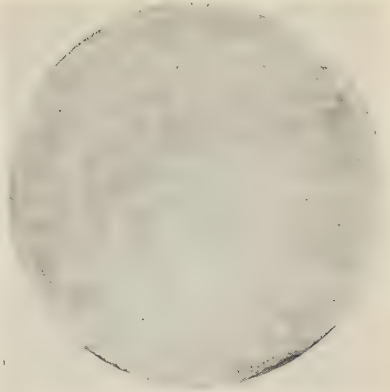


FIG. D.—Sulphur print from face B.
(See Fig. B.)



FIG. E.—Sulphur print from face C.
(See Fig. B.)

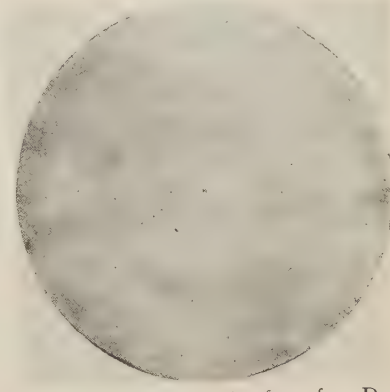


FIG. F.—Sulphur print from face D.
(See Fig. B.)

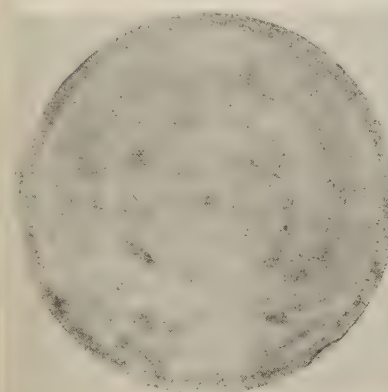


FIG. G.—Sulphur print from face E.
(See Fig. B.)

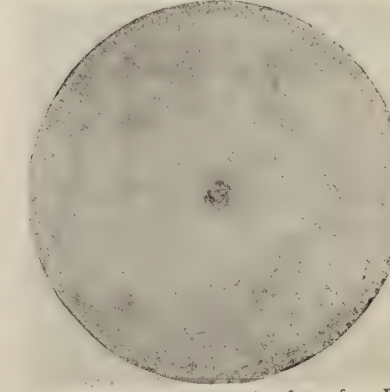


FIG. H.—Sulphur print from face F.
(See Fig. B.)

[To face p. 270.]



FIG. J.



FIG. K.



FIG. L.

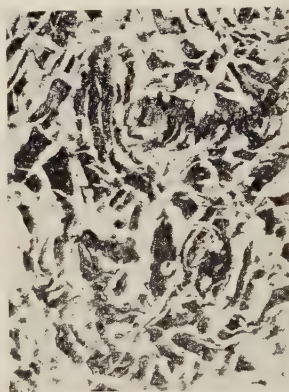


FIG. M.

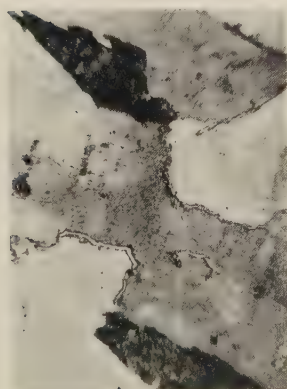


FIG. N.

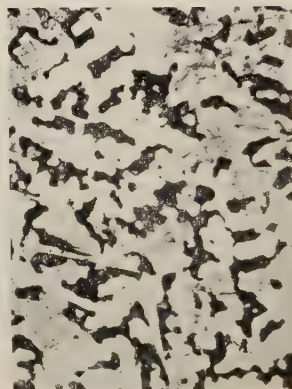


FIG. O.

Magnification $\times 50$. Reduced in reproduction to five-ninths.

[To face p. 27]

3½ times the average lateral dimension; also that by a reduction in section in the downward direction at a critical rate, axial weakness was reduced to a negligible degree, always assuming a reasonable feeder-head was provided and casting and other conditions were satisfactory. Further, with exceptions, the Committee believed that a cylindrical ingot of the shape indicated could not be cast under such conditions without developing high internal stresses. Incidentally, it was not a suitable shape for the production of many forgings. It might also be added that the method would prove costly, since it would appear that what was in fact a special furnace had to be prepared for each ingot.

The successful casting of large masses of steel was dependent upon many complementary factors, and the merit of the authors' experiments was that they had very boldly dealt with certain aspects on unorthodox lines. It was largely by such experiments that the technology of the subject could be advanced, but, in the opinion of the Committee, the results presented did not, at this stage, indicate that the objects which the authors had in mind had been achieved.

Mr. T. M. SERVICE (Glasgow) thought the Committee on the Heterogeneity of Steel Ingots should feel very grateful that, as a consequence of their publications, interest in the manufacture of steel had been aroused, not only in the people who carried out the work but also in the users, and the paper under discussion was a user's idea of casting in order to improve quality. It showed the results of an investigation, by similar methods of examination to those adopted by the Committee, of an ingot made by the new principle adopted by Sir Charles Parsons.

It was an undoubted fact that ingots as at present made required improvement; there were four bad defects, and each or all of them had a harmful influence on the resulting product. The four defects were:

- (1) Axial weakness. That, in some cases, was only intercrystalline weakness between the grains, but in other cases it was an actual crack, sometimes accompanied by larger or smaller contraction cavities.
- (2) Axial segregates, usually accompanied by some non-metallic inclusions.
- (3) The inverted cone type of segregate, lying between the centre and the outside.
- (4) Non-metallic inclusions, which might occur anywhere in the ingot, and had no fixed position or fixed area.

Taking the defects in the order outlined:

(1) *Axial Weakness*.—Having carefully examined the actual centre of the ingot, he could say that that defect did not exist in the Parsons ingot. Etching by copper ammonium chloride solution, which was

the most drastic method known for detecting intercrystalline weakness, did not reveal any trace.

(2) *Axial Segregation*.—Neither by a sulphur print, nor by etching by copper ammonium chloride, was any trace of axial segregates detected.

(3) *The Inverted Cone Type of Segregate*.—That type was minimised and the position altered. On comparing Fig. 6 (Plate XXVII.), the surface etched by copper ammonium chloride, with Fig. 5 (Plate XXVI.), the sulphur print, the cone type of segregate was detected in the crystals growing at right angles to the vertical walls of the mould; none of those segregates were detected in the crystals growing vertically from the bottom.

His (Mr. Service's) opinion, based on the evidence produced from the ingot which had been obtained by methods adopted by the Committee on the Heterogeneity of Steel Ingots, in respect of the three types of defects given above, was that the Parsons ingot was superior to the present type of ingot produced by the orthodox methods of manufacture.

(4) *Non-Metallic Inclusions*.—On that point he had an open mind. He did not see, at present, any reason why an ingot cast by that method should contain less inclusions than one cast by the orthodox methods. It might be supposed that owing to the long time the ingot took to become solid—14 hr.—a certain proportion of those inclusions would rise to the surface, but that did not appear to occur to any great extent (see Figs. 10 and 12, Plate XXX.; Figs. 16 and 17, Plate XXXI.; and Fig. 21, Plate XXXIV.).

Dr. McCance, in his paper on non-metallic inclusions given before this Institute in 1918,¹ had calculated the speed at which inclusions rose to the surface, and also the percentage of particles of a definite size (2.0×10^{-3} cm.) at various temperatures above the melting point, and his results showed that a large percentage of inclusions were retained in the ingot. The amount of inclusions in steel was bound up with steelmaking, temperature, erosion of brickwork, &c., and, he (Mr. Service) thought, could not be influenced, to any great extent, by the type of mould into which the metal was cast.

Sir ROBERT HADFIELD, Bt., F.R.S. (Past-President), said the members were greatly indebted to Sir Charles Parsons and Mr. Duncan for a very interesting paper. Dr. Hatfield had put before the meeting a point of view with regard to the larger ingots, and that of course was most important, but he hoped the authors would continue their experiments and show what was the bearing of their methods upon smaller masses of steel, for it was well known that it was not only with large masses that troubles arose occasionally, but that it was equally important to have smaller masses perfectly sound. He mentioned that

¹ *Journal of the Iron and Steel Institute*, 1918, No. I. p. 239.

because his own experience in very large ingots had not been very great, but between the years 1910 and 1915 he had presented a considerable number of papers on the subject of sound steel to the Iron and Steel Institute, the American Institute of Mining Engineers, the Franklin Institute, and other bodies, dealing very fully with that problem. He ventured to think that the information there presented and the discussions which had followed had largely helped on the production of sound steel during the last ten to fifteen years.

He felt sure it would be of interest to Sir Charles to know that an immense number of ingots, blanks, and other forms had been so produced in the years of the Great War. For example, at his own company's works close upon ten thousand 9·2-in. high-explosive shells weekly had required some 5000 double blanks or ingots—that was, two shells to each ingot or blank. He was glad to say that he had never heard of a single failure through unsoundness, segregation, fissures, or other defects. That showed that the problem of producing sound steel had been mastered for smaller work.

Regarding the general application of his system for producing sound steel ingots, he would like to make reference to an important experiment on a 25-ton ingot made by Charpy on the Hadfield lines.¹ The ingot was of octagonal design, measuring 40 in. at the upper end where the feeding-head joined. The total length, including the feeding-head, was 10½ ft., and the net length of the ingot, after discarding the feeding-head, was 7½ ft. The ingot, a section photograph of which was reproduced¹ (*loc. cit.*, p. 75), had the following analysis: carbon 0·40, sulphur 0·02, phosphorus 0·04, and manganese 0·45 per cent. The sectioned ingot was carefully examined for segregation, and appeared to be remarkably satisfactory in that respect. At the time, Charpy considered that in order to eliminate all faults and sponginess it was only necessary to cut off about 12 in. from the upper part—that was, about one-twentieth of the total weight of the ingot, as against one-third, which was the proportion of discard ordinarily required. The average waste or unsound material in that large ingot was therefore of comparatively small amount.

He could also give other instances concerning larger masses—for example, the production of sound steel used in the manufacture of 18-in. armour-piercing shell requiring 20-in. diam. circular blanks, during the war. Those comparatively large masses of material had to be rendered extremely hard—over 600 Brinell ball hardness—and then tempered. Those searching operations quickly detected the slightest unsoundness or segregation, and he was glad to say that owing to the methods he had introduced no trouble from cracking or spontaneous fracture had been experienced, either in his own works or subsequently in the employment of those projectiles. He only mentioned that to show that they had on the whole obtained most satisfactory results.

¹ A full description of this is found in the *Journal of the Iron and Steel Institute*, 1912, No. II. pp. 11, 40.

He might mention one further important instance where, notwithstanding what he had just said in relation to the production of smaller masses, there were still many difficulties met with. Taking, for example, railroad requirements in certain other countries, apart altogether from our own, there had been very serious losses of life and costly damage owing to breakages of rails in service. In the United States, for instance, the exceedingly heavy traffic (some of the locomotives there, with their huge tenders, weighed over 400 tons) imposed extremely severe strains upon the steel. Therefore it was of the utmost importance that the ingot should be sound and free from defect. He would like to ask Sir Charles, therefore, if he could carry out some experiments on smaller ingots and show in what way that unsatisfactory experience in America could be avoided. In this respect, some 12 years ago he had been asked to prepare 100 tons of ingots by his particular sound-steel method. They were sent over to America, and he was glad to say that they produced entirely satisfactory and sound rails. The discard from those ingots had not been more than 12 or 14 per cent., and exceedingly severe tests had been carried out by Dr. Burgess, Director of the U.S. Bureau of Standards in Washington.

He would like to suggest one other point. In the manufacture of large ingots was enough attention paid to the purity of the material employed? By that he meant extreme purity. In his own company's works he had recently examined the records of a large number of heats of special steel, the average analyses of which showed not more than 0.012 per cent. of sulphur and 0.017 per cent. of phosphorus—that was, under 0.03 per cent. of the two impurities or metalloids combined. All knew that the less metalloids there were present in the first instance the less difficulty there would be with segregation and the other troubles mentioned in the paper.

In conclusion, he hoped Sir Charles in replying would state what was the cost of the process as applied to, say, semi-large ingots weighing 15 to 30 tons each; to medium sizes, say, 5 to 10 tons each; to smaller sizes, say, 2 to 3 tons each, and to still smaller size ingots of from $\frac{1}{2}$ to 1 ton, which comprised a large portion of steel production. Such information would be of considerable service.

Mr. E. H. SANITER (Vice-President) pointed out that in Sir Charles Parsons' method there was nothing which had not been tried in the past; it was merely a combination—a very clever combination—of various methods, but it seemed to have produced a result which at least deserved very serious consideration. He would like to point out that the round ingot had been used for many years, and the reason it had not been employed to a greater extent was that, owing to its shape, it set up such enormous stresses in the steel that there was considerable difficulty in avoiding cracking. Sir Charles had probably done away with one difficulty in that respect by heating the walls of his mould,

but he had not done away with the possibility of enormous stresses in the centre of the ingot which, he understood from Dr. Hatfield's remarks, manifested themselves by something like a rupture.

The question of using oil burners or gas burners for keeping the head liquid was quite old. He had himself been making 20- and 25-ton ingots for the last fifteen years, using that method.

It was recognised in all steel circles that the shorter the ingot could be made the better it was. He spoke comparatively there, because he thought that the point of originality in the authors' method was that they made the ingot shorter than it was wide. He did not know of any other instance of the use of that method except in making what were known as cheese ingots for tyres. The chill bottom had naturally always been there, the only difference being that, with the length adopted for the ingot, it gave a better effect. Another method in use was the ingot cast with the big end up, which was quite a big step in the direction Sir Charles was going of causing the setting of the ingot to take place from the bottom.

Sir Charles had also lined the sides of his ingot with bricks. That, as Dr. Hatfield had already said, was quite an old method, and had caused serious trouble. Personally, he feared that the dendritic structure of an ingot so made would not give the best results, because no amount of forging would destroy the original dendritic structure.

The herring-bone segregate had been referred to, and was said not to be present in ingots made by the authors' process. The herring-bone segregate, however, was merely the sagging down of the central part as the ingot set. It seemed to him, looking at Plate XXX., where the white lines (which had not been clearly explained) were shown, that those white lines were the signs of the herring-bone segregate, but that instead of being herring-bone it had become horizontal, owing to the shortness of the ingot and the large cross-section over which the sagging down took place.

He hoped the authors would go on with their experiments. He thought that something would come of them, and that if an ingot which was perhaps a little longer than the authors', but not so long as formerly, were produced, it would be better than the best ingots which were produced to-day.

Professor J. H. ANDREW (Glasgow) said it had been his privilege to be supplied with sections from the ingot for the purpose of making a micro-examination. He had made that examination on two vertical sections from top to bottom of the ingot, one taken from the outside and the other from a position about 6 in. from the centre. The results had been submitted to Mr. Duncan with the idea that he should use them in the paper, but Mr. Duncan had sent them back with the request that he (Professor Andrew) should contribute them to the discussion.

Fig. J (Plate XXXVB.) showed one of the many segregates which he had found in the ingot. The position of that segregate corresponded

to the position of Fig. 21 (Plate XXXIV.) in the paper. That inclusion was exceptionally large, and he would like to ask the authors why, if the metal was sufficiently liquid for so long a time to allow the segregates to coalesce to such large masses, they did not float to the top?

The question of internal stresses had been mentioned by one or two speakers. Figs. K, L, and M showed very strong evidence of internal stresses in the piece taken 6 in. from the centre. Several patches of peculiar distorted structures were observed. The ferrite could be seen crinkled up, and the pearlite was also considerably distorted.

Another peculiar type of inclusion was shown in Fig. N; it appeared to be a band of cementite. He did not think it was cementite, however, because it always existed in a carbonless area. He thought the bands were some form of silicate. In one or two cases they were very markedly evident.

Fig. O was reproduced in order to show that the impurities should have had an opportunity of floating to the top. The micrograph was taken from an area practically at the top of the ingot. Both the outside section and the centre section showed precisely similar structures. It could be seen that the pearlite had been rounded into a very nodular form. That meant that the metal must have taken a very long time to become solid, so that ample opportunity should have been given for the impurities to float to the top. The question was: Why had they not done so?

One point which he noticed was the extraordinary segregation of carbon, not as revealed by the authors' analyses, but as revealed by their microstructures. If an ingot were cast and allowed to grow cold very slowly, a marked segregation of the ferrite and the solid solution was bound to result. Immediately after casting, that segregated state would exist, and he contended that there was a very small amount of diffusion on a falling temperature. The analyses of an ingot did not really give a very good impression as to the amount of segregation of carbon. Further, at the bottom of the ingot the whole mass was almost pure ferrite. Were the authors, by that process, going to get that segregation every time? That was to say, would they find that when they forged certain of their cheeses some would be of a lower carbon content than others? He would like to know whether that analysis had been made. He did not for a moment wish the authors to regard that as a criticism directed against their method of casting; it was merely a point concerning this particular ingot. He understood from Mr. Duncan that many changes had been made, and that they were now able to get a sound casting. As a first attempt it had been remarkably successful.

Dr. W. ROSENHAIN, F.R.S. (National Physical Laboratory), said that, like everyone else who was interested in what took place when metal solidified, he had been very much struck by the great interest

and importance which attached to the experiment described by Sir Charles Parsons and Mr. Duncan. Sir Charles, in his opening remarks, had referred to the casting of specula, and it had struck him (Dr. Rosenhain) that the present was one of those cases where knowledge derived from an entirely different source had been applied in a scientific manner to make an attempt at solving a problem of a very different kind.

Whatever might be thought of the success which had been attained in those earlier attempts, it was quite clear that important knowledge, at any rate, of the formation of ingots and segregates in them would be gained as the result of an experiment of the kind under review. Looking at the matter from that point of view, he was inclined to ask what was the justification for the scientific idea at the base of the experiment, that an ingot, in order to be satisfactory, should be solidified from the bottom upwards? He took it that what was really at the back of Sir Charles' mind, beyond the fact of experience that in the specula good results were obtained in that way, was perhaps the idea that the junctions of crystals were in themselves sources of weakness. That, if he might say so, was inherently a fallacy. The actual fact was that junctions of crystals, if they were free from impurity, were stronger than the crystals themselves—were sources of strength and not of weakness. But quite apart from the segregations in the example shown, there was another difficulty, and that was that where crystals met there was a tendency in a cast material for impurities, both solid and gaseous, to accumulate. He thought that the real cause of the success of the specula to which Sir Charles had referred lay in the fact that the mode of solidification was eminently suited, not so much to the prevention of segregation, and by no means, in his opinion, to the formation of a favourable crystal structure, but mainly to the opportunity for the elimination of gas from the crystal boundaries; and he ventured to suggest, further, that it might well be found that the rather striking mechanical tests which the authors obtained with their ingot might be due more to the fact that the extremely slow and more or less uni-directional solidification had allowed the expulsion of gas from the metal, than to any changes, which he did not think were really so very striking, in the distribution of segregates. His reason for making that suggestion was that for some years past, in the laboratory with which he was connected, they had been working at the problem of the elimination of gas from solidifying metal, with a view to the production of sound castings. They had had the good fortune to work with metals much easier to handle than steel—perhaps even more prone than steel to take up gases at every possible opportunity, and to produce those gases in the form of cavities in the most undesirable places—and they had succeeded in getting over that trouble in a simple manner.

He thought the industry which worked with those particular metals had applied their methods successfully in practice. There were two different ways in which that result had been obtained. One of

them did not concern the present issue, and he would not refer to it, but the other did—that was the method of allowing the metal to solidify very slowly. For that purpose the metal was melted in the ordinary way. It did not matter how gassy it was—sometimes it had been gassed intentionally. It was then allowed to solidify slowly in the furnace—in the case under discussion in the crucible or in a suitably preheated mould. It was then quickly remelted and cast, and the resulting product was entirely free from the pinhole cavities and the general defects which were so very common in that particular metal under ordinary conditions. The circumstances were such that it was possible to observe what happened. As the metal cooled, the surface showed the rising of bubbles, something like the last effervescence from an aerated liquid. One saw the bubbles bursting on the surface, and the effect on the density of the material and on its mechanical properties was very striking. It occurred to him that in the slow solidification from the bottom upwards which had been achieved in the method of casting steel under discussion, something very similar must happen. There was not apparently time for the non-metallic impurities to rise to the surface. One forgot sometimes that the difference of density was not so very great there, and therefore the upward tendency was not so powerful as one would anticipate. But gas stood in a very different position, and he thought the conditions of solidification were such that they would certainly tend towards the elimination of gas, and in that way were bound to produce desirable results. A countervailing fact was the fact that such slow-cooling produced inevitably a very coarse crystal structure, a coarse macrostructure, which no amount of subsequent forging could eliminate, and he should anticipate that in forgings made from ingots of that kind one would find a coarse banding—a banding which one knew so well in mild steel and materials of that kind—which was nothing more or less than the descendant of the coarse segregated crystals themselves. He was speaking now of crystal segregation, and not of the mass segregates to which the authors had referred. That was an inevitable consequence of the very slow solidification which this method implied, and he thought was perhaps in many respects its most serious disadvantage.

There was another disadvantage, and that was the formation of what was, he thought, quite inevitably a crust on the surface of the metal as it rose in the mould. In ordinary ingot casting one saw that crust rise, and in successful cases it rose steadily without becoming either tilted or broken up. He should imagine that the difficulty of securing a steady rise of crust on an ingot of that size would be enormous. If that crust did not rise steadily the consequences were rather serious, because the oxides and other impurities which were formed on the crust became entangled with the metal and could not release themselves satisfactorily.

He would suggest as an alternative to the scientific idea which

Sir Charles had used another principle altogether concerning the proper mode of solidification of metal in a mould of any kind. First of all, the greatest possible purity of the material should be aimed at so that there should be nothing to segregate except carbon, and perhaps manganese, which did not segregate very much. The really damaging segregation was due to the presence of impurities, and particularly to the presence of those non-metallic enclosures, which could be eliminated if it was worth while in other ways, as, for instance, by holding the steel in steady fusion for a sufficient length of time before casting it at all (possibly an expensive method). But, granted some sort of preliminary treatment of that kind, and a sufficiently pure metal, he thought that the sound method of solidification was to avoid contraction difficulties by never having in the mould at any one time more than the minimum amount of liquid metal; in other words, filling at a rate just sufficient to keep pace with solidification and sufficient to prevent cold-shutting at the edges of the mould. He could see there were very great difficulties in carrying that out in practice, but where it could be done—and he had tried it on a small scale—it had immense advantages, because the amount of liquid which could contract at any one moment was small, and therefore there was no formation of anything in the nature of piping, and there were not the possibilities of movement and segregation which existed in a large mass of liquid undergoing gradual solidification. The material would be kept very nearly as homogeneous in the solid state as it was in the liquid at the outset. The practical difficulties, he admitted, were great, but he was not sure they were very much greater than in the somewhat revolutionary method which Sir Charles Parsons and Mr. Duncan had put forward.

Mr. B. TALBOT (Past-President) said that for many years he had done considerable research work on ingots, but without getting the price for the finished product which Sir Charles Parsons would get for his. The Institute was greatly indebted to the authors for their most valuable experiment—for it was still, he thought, an experiment. Once again it had happened that a brilliant intellect from outside had been brought to bear on the iron and steel industry and its problems. That was not a new experience, for Bessemer, Siemens, and Thomas were not brought up in the industry. The authors had undoubtedly produced a very uniform ingot by their method, which, when applied commercially for the particular purposes they probably had in mind when starting their experiments, would no doubt prove superior to others.

Personally, his own work had been directed towards trying to improve the quality of the cheap ingot, which, after all, was employed in 90 to 95 per cent. of the world's uses. He ventured to think that if and when Sir Charles went further and tackled that predominant portion of the industry he would find it necessary to have an ingot which was

longer in its vertical section than in its cross-section ; in other words, it would have to be exactly the opposite of what the authors were using to-day for their particular purposes, if rolling-mills were to be employed. Personally, he dreaded to think what would happen to his mills if he put in an ingot of small vertical height as against very large cross-section. That, however, was a practical engineering difficulty.

Then there was the question of the cost of casting ingots in the brick-lined moulds illustrated, and what kind of output would be obtained if the ingots had to be kept liquid as long as possible ; the method might not be suitable for the cheap trades using the kind of ingot necessary for rails, &c. His own view was that a reasonable quality of steel could be obtained for those purposes by the methods adopted by Sir Robert Hadfield and others by keeping the tops open ; and, as Mr. Saniter said, one very often cast the ingot with the large end at the top, which tended to bring the segregates to the top as the smaller end of the ingot solidified first.

The whole problem in the end would have to be settled as the authors suggested in the last paragraph of their paper. Everyone agreed that if steel could be obtained free from segregation and axial weakness it was to be preferred—there was no argument about it ; but it must be at a reasonable cost.

Mr. W. H. PATCHELL (London) thanked the Institute for letting him, as a non-member, take part in the proceedings. One was struck by the novelty of a man like Sir Charles, who was not a steel-maker, coming in to teach steel-makers how to cast their ingots.

Full confidence of the buyer in the seller was the essence and the foundation of the iron and steel business, but sometimes one received a shock from the disclosure of hidden flaws. In Sir Charles' case, and in that class of business in which he himself was most interested, it was the maker, not of the steel, but of the machine who received the blame. Personally, he was more interested in longer forgings than those with which the authors had dealt. A short time ago one of the largest machine-makers in England complained, at a meeting of the Institution of Electrical Engineers, that " We are waiting for forging makers to make sound forgings from known materials." That was so not only in Great Britain but in the United States. In the United States he had seen shafts 20 ft. long and of 28 in. maximum diameter made for large steam turbines—larger machines than existed in this country up to the present, though he hoped they were coming here too. Those shafts had not been altogether free from reproach ; they did not always " stay put." There must have been internal stresses, and the trouble which had occurred with those shafts had led to discussions between the steel-maker or forger and the purchaser, with the maker of the machine occupying an intermediate position. One was led to wonder what went on in those shafts. If the ingot was

chosen for the job, uni-directional forging might be adopted, with or without upsetting. Some people were greatly opposed to upsetting.

Sir CHARLES PARSONS, in reply, said Dr. Hatfield appeared to be of opinion that very heavy stresses would be produced in casting in a disc form. There were two kinds of stresses, sheer and bulk. Sheer stress depended on the temperature gradient in the metal as it set; that was a fundamental thing in mechanics. The disc would relieve itself to a certain extent by trying to buckle. The only way in which it could really be proved was this: Speculum metal was one of the most brittle substances that existed—it was more brittle than glass; when a speculum, 6 ft. in diam., about 5 in. thick and weighing about 4 tons, cooled it did not crack. It was cooled, of course, very slowly indeed, and very slowly annealed, but it was practically set before its temperature was allowed to sink. That proved there could not have been great sheer stresses in the speculum metal.

Coming to the bulk stresses, if a mass were cooled rather rapidly by external radiation the outside set first. The outside having set, and the inside being molten, or much hotter, it started to contract; as the outside shell was rigid, rupture or cavities were bound to take place in the centre, and therefore segregations and weak places were produced in the centre of the mass. When a long ingot cooled in the cylindrical fashion, cavities were bound to occur in the middle, because the metal contracted and was bound to leave a vacuum; but when it was cooled in horizontal layers no bulk stresses were produced; there was simply a sheer stress, and the speculum metal proved that that could not be very serious.

He would ask Mr. Duncan to deal with the other matters raised in the discussion.

Mr. DUNCAN said the authors were grateful to all those who had taken part in the discussion, because they felt that criticism would aid progress. To the authors it was very important to be able to obtain forgings, both of small and large dimensions, on which they could rely.

The experiments described were undertaken as the direct outcome of the First Report of the Heterogeneity Committee, in which the Committee showed the defects present in steel ingots made under the best conditions. Dr. Hatfield had said that the example taken by the authors from that First Report did not represent the state of the art to-day. He did not know that that example had been cast many years ago; he had thought it was (as stated in the paper) a representation of what engineers must expect and look for, and he was really under the impression that users were told they were unreasonable in their demands, because steel could not be cast in large masses free from cavities and from segregate.

He gathered that Dr. Hatfield and the Heterogeneity Committee

were of opinion that (by using such methods as pouring at the correct speed, correct variation in the cross-section from top to bottom, ensuring the correct temperature of the metal, and other refinements) axial weakness had now been reduced to negligible proportions. If Dr. Hatfield would come and spend a month or two at their works, and make himself responsible for getting their contracts through to time, he would find that defects in steel forgings were far from negligible, and all too frequently delayed the completion of the contract. The Chairman of the Forgemasters' Association told turbine builders at a joint meeting a few years ago: "Gentlemen, you must not go in for larger forgings; you have reached the limit, and you must moderate your demands. If you do not, we must warn you that the segregation effects and the axial unsoundness will be increased. In fact, we think you ought to put a 12-in. hole through each forging to remove that weak centre." A 12-in. hole was, however, quite out of the question; the turbine builders had, therefore, to compromise and put through a 3-in. or 4-in. hole, which they found did not remove this weakness in many cases.

Dr. Hatfield said—and the authors took it to represent the considered opinion of the Heterogeneity Committee—that the method employed by the authors had one effect which was serious—namely, that it left the major segregate at the top corners and would necessitate a large discard. The authors agreed with him and the Committee. They thought that was a very serious effect, but what, they asked, was to be thought about an ingot cast in the ordinary way, in which that major segregate was left in the ingot and in the forging, and could not be removed by any amount of discard? He thought the Heterogeneity Committee had shown the necessity for the very experiments the authors were carrying out.

Dr. Hatfield also referred to the white bands, and wanted some more information about them. The authors had analysed and examined those bands microscopically, and had found they contained less carbon, less phosphorus, and less sulphur than the adjoining material. He thought Mr. Saniter's explanation of them was probably the correct one, but the authors did not feel qualified to express an opinion on the subject; they accepted Mr. Saniter's explanation.

The question of the slow cooling and the very coarse crystal structure produced had been referred to. That was criticised by several members, some of whom were afraid that the coarse structure would be a source of weakness to the mechanical properties. Dr. Rosenhain had emphasised that. He was not sure how Dr. Rosenhain reconciled that statement with the mechanical tests which the authors obtained from the forging after it was cut into cheeses and forged into discs. There the authors showed that, whatever the coarseness of the structure, the mechanical properties in three directions were better than anything which could be obtained from steelworks to-day with ingots cast with all their skill in the ordinary way. If the coarseness of the crystal structure was such a detriment to the mechanical properties one would

expect to find it shown. The authors did not find it, and their tests were taken close to the centre of the discs.

Dr. Hatfield said his Committee would have liked some information about the tear. Surely Dr. Hatfield and his Committee must know that if any ingot of the section in question, whatever its shape, was cooled as rapidly as the authors cooled theirs (because although they expected it to tear they thought it unimportant, since they proposed to cut up the ingot for examination) there was bound to be large internal stress. The second ingot was cast and treated in the normal manner—that was, slowly cooled—and it did not tear. One would never allow an ingot, even of the ordinary shape, to be cooled rapidly. After it was cast it should be stripped while the outer surface was still at red-heat and charged immediately into the forge furnace.

The question of difficulties of manipulation had been raised. The authors agreed that was a difficulty, but they found no difficulty whatever in casting a stalk on the ingot after it had set, and they could assure Dr. Hatfield that that stalk did not break off at the root during the subsequent forging. A simpler method would be to lower a bar, perhaps heated up to welding heat at the end, into the metal just before it set, in the same way as at the present time lifting hooks were lowered into large ingots.

Dr. HATFIELD, interposing, said that would mean a chill at the top.

Mr. DUNCAN agreed, but said it would be in the segregate portion and would only penetrate 12 or 15 in., which portion would be discarded.

A question had been raised with regard to the illustration given in the First Report of an ingot cast in a loam mould, and with regard to the faults to which that method of casting had given rise. He did not think that was a parallel case with the authors' ingot. In the first place, the loam mould was not heated; in the second place, the top was not kept hot; and, in the third place, the chill on the bottom was not nearly of sufficient dimensions to ensure that the cooling proceeded from the bottom only.

With regard to the shape of the ingot, Dr. Hatfield wanted to know whether the authors would make their moulds to suit the forging, or the other way round. The whole principle, of course, depended on cooling from the bottom, and therefore they proposed to adhere to the present shape. In the case of the second 20-ton ingot cast, it was forged from a 70-in. diam. into a 40-in. diam. bloom in one heat. One then had a bloom of the ordinary shape, and it was well known that an ingot cast in the ordinary way had to be bloomed also in the first heat.

Mr. Service very clearly and concisely pointed out four bad defects which were found in present-day ingots. The authors agreed; they were constantly coming across those defects. They were glad Mr. Service agreed that several of those defects had been overcome by

their method. In the first ingot cast by that method they did not expect perfection, but by giving attention to details and learning by experience they expected to improve it very considerably, and they hoped at some future date to be able to give to the Institute the result of further experiments.

The authors thanked Sir Robert Hadfield for his kind remarks. The only information they had concerning smaller ingots was in regard to the 3-ton ingot, 3 ft. in diam., a sulphur print of which had been shown, but as the principle was the same they would expect similar results from any size of ingot.

The authors were of course quite aware of the great amount of work which had been done, and the experiments which had been carried out by Sir Robert Hadfield, by Mr. Talbot, and by others, and had benefited greatly by reading their various contributions to the subject. They were not, however, thinking of competing at all with the work those gentlemen had done; their object was rather different. There could be no question but that their method would add to the cost of making rails, for example, because one would have first of all to bloom the ingot and then cut it up into cheeses of the size required for the small ingots, and that would certainly add to the cost. Whether it would be worth it or not was quite another matter.

The question was also raised of the cost of the mould, and of providing a new mould for each ingot. The cost of a hematite mould as used in the ordinary method was large, and after thirty or forty heats it had to be scrapped. The authors did not know how many heats it would be possible to get out of one mould built in the way they described, but steelmakers had plenty of experience of the life of ladles, and it was well known that all that was needed was to patch up the brickwork. That was not costly, and the first cost of making the mould was not high at all. Even with the ordinary hematite iron moulds the inside had to be cleaned each time and given very thoroughly a protective coating, so he did not see why the mould used by the authors should prove more expensive. After the first ingot the mould stripped absolutely clean and was ready for another charge; there was no difficulty about it at all, and the mould walls were in perfect condition.

It was too early to say anything about the cost of the process at present, but it was difficult to see why it should be any more costly than the ordinary method of casting large ingots.

The authors quite agreed with Mr. Saniter that their method was really a combination of old methods; it was the combination that they were claiming. He felt sure Mr. Saniter's difficulty about round ingots and the cracks which had been experienced in the past, would not arise in the present case if the ingot was taken at a red heat to the forging furnace, or was slowly cooled.

The authors thanked Professor Andrew for his contribution to the discussion and for the very interesting micrographs which he had shown.

The strained structure shown was to be expected on account of the very rapid cooling to which the ingot was subjected.

No analyses were made of the cheeses, but the pieces which had been cut out of the centre still existed, and no doubt the authors could analyse them and determine the amount of segregation.

Dr. Rosenhain was of opinion that the good mechanical tests were due to the expulsion of gases. The authors did not know; all they wanted was to obtain a material which would give the results realised, and he could assure Dr. Rosenhain that it was a very difficult problem to obtain such material with regularity.

With regard to non-metallic inclusions, at a meeting of the Institute a few years ago the question of non-metallic inclusions and their rising to the surface was discussed, and it was mentioned that their size was so small and the rate of freezing of the ingot was so fast that they had no chance of reaching the surface. Now Dr. Hatfield complained that the authors had cooled their ingot so slowly that the non-metallic particles were very large. Naturally they were; they had had time to coalesce, and cooling the ingot very slowly from the bottom gave them greater opportunity of getting to the top. One could not have it both ways; either it must be favourable to the process, or the other explanation given was wrong. The authors thought the amount of cooling taking place on the sides of the first ingot prevented a lot of particles from getting to the top which would otherwise have got there. Moreover, Fig. 21 (Plate XXXIV.), showing the non-metallic inclusions, and Professor Andrew's Fig. J (Plate XXXV.), were taken from one of those pieces of crust which had got trapped in the ingot, and not from a white band.

He had forgotten to mention that in the authors' opinion they made a great mistake, when casting the first ingot, in pouring it so slowly. The teeming from a $1\frac{1}{2}$ -in. nozzle was far too slow for an ingot of the diameter in question. He did not say it was too slow for an ingot cast in the ordinary way and of the ordinary dimensions, because it was most important in that case that the teeming speed and the temperature of the metal should be carefully adjusted. One would get that cone-shaped formation at the bottom of the ingot by casting too hot. With the authors' method nothing of that sort could occur, and one could cast as fast and as hot as one liked in fact, the faster the better, because the larger the stream the less the oxidation from the furnace to the mould, and therefore the smaller the amount of non-metallics. There was nothing to fear in the way of crystal formation, cracking, or anything of that sort due to teeming too fast.

He thought the difficulty about the crust might be got over by filling the mould with nitrogen or another inert gas. He had heard of that being done in the case of armour plate, with a great reduction in the amount of crust formed. Such things should not be insuperable difficulties.

The authors were glad to hear Mr. Talbot's opinion that the ingot

was a most uniform one, because they valued his opinion very highly. Mr. Talbot went on to show that the shape of the ingot was not suitable for rails, &c. The authors quite agreed with him.

The authors would deal with other points in a written reply.

This paper was also presented at the Additional Meeting held at Glasgow on May 9, 1929.

Professor J. H. ANDREW (Glasgow) said that in the second paragraph on p. 257 there appeared the rather peculiar sentence: "Fig. 5 (Plate XXVI.) is a sulphur print of a longitudinal section of the ingot at its central axis; the white bands are areas of lower carbon and phosphorus content." That was the first time that he had ever heard it suggested that a sulphur print gave an indication of the carbon distribution. In the first place, areas low in carbon were invariably high in phosphorus and sulphur, and would be represented by the dark areas in the sulphur print. He thought the sulphur prints of the cheeses were some of the most beautiful that he had ever seen.

Mr. T. M. SERVICE (Glasgow) said that the first lantern slide¹ shown by Mr. Duncan in presenting the paper illustrated what was commonly found in steel ingots made by the present-day methods when split and sulphur-printed. It had been stated at the London meeting of the Institute that ingots as now made were not so bad as that shown in that slide, but the improvement was only a question of degree. All present-day ingots showed the same type of defect, and, although improvement had been made, the central weakness was still present, and there was always a certain area near the bottom end which either showed definite cracks or a weakness which on working ultimately became a crack. In Sir Charles Parsons' ingot, however, there was no central weakness, so that so far as solidity was concerned that ingot was an improvement on what was produced by the ordinary method of casting. Segregates were absent from the greater part of the ingot, but there were traces to be found at the top right- and left-hand corners of the ingot. With regard to non-metallic inclusions, there was one particularly dark line which contained inclusions (see Fig. 21). He did not suppose that inclusions could be got rid of entirely; their quantity and position were bound up with the method of manufacture and the casting conditions, and were little influenced by the time of cooling. Unless those segregates were fairly large in extent they never floated to the surface.

There was one point which Mr. Duncan should make clear—namely, that that type of ingot was only suitable for certain classes of material.

¹ See "Report on the Heterogeneity of Steel Ingots," *Journal of the Iron and Steel Institute*, 1926, No. I., Fig. 1, Plate II.

For the ordinary mill product, as it was known in the West of Scotland, that type of ingot would be unsuitable, and consequently for the majority of steel produced in the country the process could not be applied.

Another point put forward at the meeting in London was that the stresses in that type of ingot were considerably greater than in an ingot made by the ordinary methods. He did not agree with that. Ingot were made even larger in diameter than 6 ft., and if allowed to cool quickly, as was done in the present case, they also would have large internal stresses. The stresses set up in either octagonal or circular ingots, if cooled quickly, were considerable, and their extent depended to a great degree on the method of cooling. A 6-ft. diam. circular ingot was no more difficult to control than an octagonal ingot 6 ft. across the flats.

Mr. J. G. McDONALD (Glasgow) desired to comment on Professor Andrew's reference to those white lines. He thought that in the present state of knowledge Mr. Duncan should leave that sentence as it was. The sulphur print suggested a drop in sulphur content, but not necessarily a rise in phosphorus content, as was shown by the analysis given opposite one of these lines in Fig. 9. The drillings were taken with a fine drill in order to avoid contamination as far as possible. There was also a drop in the carbon content, as was to be expected from the appearance of the same lines on the nitric acid etching, Fig. 19, and that was confirmed by micro-examination. The simple explanation of the presence of those lines was that they were composed of metal definitely freer from each of the three segregating elements than the surrounding metal.

The CHAIRMAN (Mr. R. Hamilton) said that at the bottom of p. 257 he had noticed the following statement: "The main segregate is only noticeable at the top, which would be discarded." Looking at the illustration, it seemed to him to be rather difficult to discard that segregate. That that ingot was not typical was shown by the next ingot which did not contain that segregate to the same extent. It was possible that that method of casting might result in very little segregate being formed, but, if there were any, he would like to know how it was to be discarded.

For the AUTHORS' reply, see p. 299.

This paper was further discussed at the Additional Meeting held at Sheffield on May 15, 1929.

Dr. W. H. HATFIELD (Member of Council), in opening the discussion, repeated the gist of his remarks made at the Annual Meeting in London (see p. 267).

Mr. E. H. SANITER (Vice-President) reiterated some of his comments made at the Annual Meeting in London (see p. 274). Continuing, he said that Dr. Hatfield had referred to the danger of sand or dirt getting into the ingot from the brick lining. He thought Dr. Hatfield might banish those fears; large quantities of steel castings were made in a somewhat similar manner, and they were produced without the fear of dirt getting into them.

He questioned whether uni-directional freezing would get rid of the non-metallic inclusions. While it might drive the segregate to the top, he doubted if it would also carry the non-metallic inclusions to the top, though the method of keeping the top hot might help in that direction.

A modification made since the paper was prepared, was the dropping of pieces of coke on to the top of the steel; unless there was an oxidising atmosphere—which he thought Mr. Duncan would not want—that coke would become more or less dissolved in the steel and make the segregation more severe.

Mr. DUNCAN said there was some slag on top.

Mr. SANITER asked if the coke were added just to supply heat.

Mr. DUNCAN replied that air was blown in.

Mr. SANITER, continuing, thought that the fusing-in of a porter bar might prevent the quiet gathering together of the segregate; the insertion of the white-hot porter bar might disturb seriously the setting of the top part of the ingot, and cause some unsoundness by introducing oxide of iron.

Mr. A. A. MUNRO (Eaglescliffe) thought the authors might be said to have carried out with a certain amount of success a fairly large experiment on sound principles; they would obtain even greater success after more experience in casting conditions, &c. It had been suggested that that type of ingot might be suitable for hollow forgings; although that appeared to be correct for small forgings, the larger ones would present difficulties, especially in casting and forging. It must be remembered that with large hollow forgings a 21 in. to 27 in. diam. core was removed. That, of course, removed all the central weakness, which was the cause of so much trouble to the turbine engineer. Secondary segregation was left in the walls of the forging (except at the top end in some cases), and was thus not affected by any of the processes for which the final forging was used. Carbon segregation was still present in the ingot, and would be of great importance in hollow forgings; it would appear as ghost lines in the bore. Segregation, as generally understood, was not seen in the ingot at all, but he

was convinced that it was still present, though in a finely divided state throughout the ingot.

Non-metallic inclusions were the greatest trouble, and he asked if the authors felt convinced that that type of ingot was cleaner than the present ingot. Silicates were carried into the ingot from the furnace and the ladle, and, by using a mould composed of bricks, an increased risk would be presented to the steelmaker, that depending, of course, on the casting conditions.

An ingot suitable for large forgings weighed between 120 and 165 tons. That would mean an ingot approximately 14 to 16 ft. in diam. by 7 to 8 ft. long. Casting a head for handling purposes would affect the cooling of the ingot. In place of a head, the authors had suggested welding on a bar before the ingot had finally set. The question arose how far would that bar have to sink in to ensure the handling of the ingot with safety? The depth to which the bar would sink would affect the amount of discard to be removed.

Forging a large-diameter ingot which was so short would be extremely difficult, as the outside diameter must elongate much faster than the centre. That, again, would increase the amount of discard. It was doubtful if there were a press in the country which could tackle the work.

The authors had stated that there was no necessity to crop material off the bottom end of their ingot. He believed the large-diameter bottom end would contain a considerable amount of non-metallic inclusions due to the sudden chilling obtained from the bottom plate.

He agreed that that type of ingot would be suitable for small hollow forgings which, at present, were made solid and bored out. In that case piping did become important, and it had caused trouble in the past.

It was to be hoped further experiments would be carried out. Provided that a clean non-piping ingot were produced at a reasonable cost, he would be prepared to accept forgings which otherwise met buyers' specifications.

Mr. E. C. IBBOTSON (Sheffield) remarked that Lord Chetwynd had carried out a long experiment of heating ladles full of steel, in very considerable quantities, both in Sheffield and in Leeds, and the mechanical tests on about 1000 tons had shown practically no advantage.

Mr. T. F. RUSSELL (Sheffield) said that it was a well-known fact that quite a large proportion of the defects in steel found their origin in the casting, and any suggested new method of casting should be very carefully examined. The method of casting as practised in Sheffield had been developed after many years of scientific observation on the effects of casting speeds, temperature of the metal, size and shape of the ingot, &c. A certain stage of perfection had been reached,

beyond which it was probably impossible to go with the usual cast-iron mould. Mr. Duncan had now introduced what was an essentially new principle—namely, the use of a mould made of a refractory material heated almost to the temperature of molten steel. The change was a drastic one, and until far more than was given in the paper was known about such things as the skin defects, amount of waste, forging properties, costs, and the many other points already raised in the discussion, it was too early for anyone to pass an opinion on it.

All metallurgists agreed that the ideal method of casting ingots was to chill the metal from the bottom and allow it to solidify upwards. Whereas Mr. Duncan was attempting to attain that object by using a badly conducting hot refractory material for the walls of the mould, a continental worker was experimenting on an exactly opposite principle—namely, the use of moulds made of good conducting, water-cooled metal. Dr. Oertel had described¹ some very interesting experiments on the casting of steels (plain carbon, tungsten, magnet steels, and high-speed steel) in a tilting, water-cooled, round copper mould, which was said to need no preparation and to have almost unlimited life. The ingots, which weighed about 4 cwt., had been thoroughly examined, and appeared in every way highly satisfactory. Dr. Oertel admitted that his experiments must be looked upon as preliminary ones, and that further tests were necessary before a final opinion could be formed on the value of water-cooled moulds. That, he (Mr. Russell) thought, should be the general attitude towards the authors' valuable experiments with hot refractory moulds.

Mr. G. E. HOWARTH (Sheffield) said it would be of considerable interest if any information on the distribution of silicates within the ingot could be given. An account had been given by Dickenson² of a number of ingots and forgings of piping steel which had been examined; in each case a very distinct increase in the silicate content was shown to exist near the bottom end. The ingots were of the usual type, cast in chill moulds, in which the solidification of the molten steel had commenced from the sides and bottom; the macrostructures showed the typical columnar skin with a lighter etching central pyramid of free crystals resting on the bottom floor of chill crystals. It was suggested that during solidification the lighter etching zone of free crystals had formed as the result of a downward shower of heavy, purer crystallites, and that the increased silicate content close to the bottom end was due to coalesced particles of slaggy matter being mechanically entangled and carried down to the bottom of the ingot by the descending crystallites.

In an ingot such as that produced by the authors, in which unidirectional freezing had taken place, commencing at the bottom face and extending upwards to close to the top, a very different distribution

¹ *Stahl und Eisen*, 1929, vol. xlix., May 9, p. 696.

² *Journal of the Iron and Steel Institute*, 1926, No. I. p. 177.

of the silicate particles would be expected, and it would be of much theoretical interest and practical importance if any information could be given on that point.

It was of interest to note that, notwithstanding the big difference in the manner of solidification, the ingot showed very similar variations in analysis to those cast in chill moulds of the usual proportions, a progressive increase in the carbon, sulphur, and phosphorus axially from the bottom upwards being found. Another point which might be of some importance with that method of casting was the large surface area of the bottom of the mould which had to be covered by the molten metal at the commencement of casting. It would appear that there was some probability of obtaining mechanically trapped oxides and blowholes in that region of the ingot, which would necessitate a considerably greater weight of discard than in ingots of the usual type.

The CHAIRMAN (Professor C. H. Desch, F.R.S.) said he would like to say a word as a member of the Ingots Committee, and one who had thereby had an opportunity of inspecting the ingot. He was bound to say that they were somewhat struck by the very marked character of the horizontal white lines, which microscopical examination showed to contain an unusually large proportion of non-metallic inclusions. He understood, however, from Mr. Duncan that that defect in the first ingot could to some extent be remedied in the later ones. There was, however, no mention of one fact : that method of casting steel seemed to bring with it a liability to a greater internal stress, and that first ingot was undoubtedly quite extensively cinked ; one would like to know whether that was inevitable in that method of casting. It seemed that the freedom from segregation might bring with it greater liability to internal stress.

He wanted to offer a word of warning as to the interpretation of one of the slides shown by Mr. Duncan in presenting the paper. It was a picture of a section of the old-fashioned ingot taken from the First Report of the Committee on Heterogeneity of Steel Ingots.¹ It had been deliberately printed rather heavily in that Report, in order to show segregation in an exaggerated fashion ; on the other hand, the authors' first sulphur print was printed unusually lightly. He did not for a moment suggest that that sulphur print was not much more uniform than that from the old ingot, but he did not want students to think that the ratio of segregation was indicated by the ratio of the depth of the two prints.

For the AUTHORS' reply, see p. 299.

¹ *Journal of the Iron and Steel Institute*, 1926, No. I., Fig. 1, Plate II.

CORRESPONDENCE.

Professor C. BENEDICKS (Hon. Vice-President) and Mr. H. LÖFQUIST (Stockholm) wrote: It has been a very great pleasure to read this paper, which contains so much valuable information; the method produces in an admirable way that desirable form of ingot which one of the present writers had called type *B*.¹ In principle, the new method, of course, does not differ very much from, say, the method of Sir Robert Hadfield, in which the upper part of the ingot was likewise heated by means of a gas-burner. The use, however, of such a shape of the mould as to give predominance to the cooling from the horizontal bottom chill is a new departure, which may prove to be of considerable practical importance. The new method can be characterised as producing the ingot type *B* with a very high, and horizontally extended, thermal centre. It may be questioned whether it would not be rational to adopt the form which is most natural for type *B*, namely, the reversed cone ¹ (*loc. cit.*, Fig. C), although stripping would probably be slightly more complicated (a divided mould would then be necessary).

As for the structure obtained on solidification, the most prominent feature is the occurrence of the well-marked transverse bands—containing oxides, and lower in carbon and phosphorus—which are essentially parallel to the horizontal cooling surface. The authors seem to attribute the oxide content only to the first contact of the molten metal with the mould bottom. The present writers scarcely think it quite justified entirely to disregard the oxidation which might take place during the whole time of pouring. The oxidation of the jet of metal might possibly be increased by the fact that the jet has to pass through a hole in the cover; this might give rise to a turbulent air motion, or injector action, which might be increased on account of the gas flame, and possibly cause a stronger oxidation than in open air. In any case, the oxidation products must be assumed to be more or less evenly dispersed in the total molten mass before solidification, and the question arises, why the oxide occurs in transverse ferrite bands. As the authors present no explanation, the present writers desire to advance the following tentative one.

As pointed out by the present writers, the solidification frequently proceeds in a periodical manner. First there is a crystallisation proceeding from the outside (in the direction of the main temperature increase), giving crystals lower in carbon, as well as in dissolved and precipitated impurities (oxide, sulphide). The foreign dissolved substances must cause a lowering of the melting point of the mother liquor, and consequently a slowing down, or even a momentary arrest, of the solidification. After this, on account of the continuous loss of

¹ See *Journal of the Iron and Steel Institute*, 1928, No. I. p. 557.

heat, a new crystallisation period will set in. The oxide and sulphide, being frequently enclosed in the lower melting residue after the earlier crystallisation, may form ghost lines rich in sulphur—in the case of the type *A*, with an inward slope of the crystal boundary, hindering the free rising in the liquid of larger sulphide and oxide particles. This explanation seems to the present writers quite satisfactory for ingots of ordinary form (extended vertically).

Now, in the case of the new ingot shape—in which the solidification proceeds essentially in horizontal layers growing upwards—another factor, which, according to the theory of the present writers, causes for ordinary ingots the formation of the “sedimentary cone,” must be considered—namely, the probable action of oxide—or silicate—particles in causing around themselves a low carbon concentration, with the precipitation of carbon-free iron, probably somewhat heavier than the melt.

Let us now consider the above residue layer, higher in dissolved elements than the average analysis, and here horizontal. The sulphide expelled from the crystallised zone below will have the opportunity of rising, on account of the sulphides generally forming larger particles and being of lower density than the oxides. Consequently, in the new ingot type, no large sulphide particles occur, except in the top parts (especially in the inward-sloping, early solidified edge portions, characteristic of type *A*).

The oxide particles—likewise expelled from the crystal zone below—will generally rise at a slower rate. Only the larger drops will rise to any extent, the smaller ones rising much less. This fact, in the present writers' opinion, may be well illustrated by Fig. 21 (Plate XXXIV.), if this be *turned clockwise through 120°*, which will then probably represent the original position with regard to the horizontal direction. Now, oxide particles of a definite size may soon be coated with a layer of ferrite crystals. In the same way as has been assumed for the sedimentary cone, *these ferrite-loaded oxide grains* will sink, forming, by sedimentation, a ferrite layer on the metal below. Without going into further details, the present writers think that, without any new assumptions being made, this gives the explanation of these horizontal ferrite zones.

Mr. H. BREARLEY (Vice-President) wrote: Although the general properties of the ingot exhibited by the illustrations in the paper might have been predictable from a reading of the authors' patent specification, the details given are to be heartily welcomed as an honest presentation of observed facts which lend support to the authors' modest statements of opinion.

The Parsons-Duncan process of ingot making should be regarded and criticised, if criticised at all, from their particular point of view. It would be unfair to ignore the paper or to belittle the process it describes because there is no prospect of using the process in the

manufacture of such steel goods as rails, girders, and fencing wire. It would be easy to cite a large number of purposes for which steel is used which could not be served by the new process of ingot-making because the market price would not permit it. It must, however, be obvious to those who will take the trouble to look beyond their immediate interests in particular branches of the steel trade that ordinary steel bought at the market price could frequently be substituted with ultimate advantage by better made steel of the same class bought at an enhanced price. Action along those lines might be fruitful in unexpected directions as it has already been fruitful in small ways when taken by people who estimate the value of steel in terms of service to the ultimate user.

I welcome the paper personally because it deals, or attempts to deal, practically with improvements in the quality of steel without raising the traditional side-issue relating to the percentage of sulphur and phosphorus in the steel, and I am entirely in agreement with the authors' preference for sulphur prints as an indication of the meaning of segregates as compared with the results of chemical analyses made on drillings taken in the ordinary way.

It might be of interest to others, as it would be to myself, if the authors could attach any meaning to the fact that the load-extension diagrams in Fig. 3 show no jog. I should also like to inquire whether it appears reasonable to the authors to suppose that the greater ductility of the test-pieces taken from the bottom of the ingot may be due to the material they represent having been drastically cooled by the bottom plate and then reheated by the hotter metal added later. An inspection of the *BL* and *BX* tests on p. 264 and a glance at Figs. 15 and 16 (Plate XXXI.) seem to favour this suggestion.

Perhaps the authors would reconsider the statement on p. 262, to the effect that the *amount* of non-metallic inclusions is usually greater in larger ingots. Whatever slag may be in the molten steel in the ladle will be neither increased nor decreased by the size of ingot mould into which the steel will flow. Slag is undoubtedly produced as a by-product of the casting operation, due to the passage of the fluid steel through the atmosphere, and this presumably is roughly proportional to the area and period of contact with the atmosphere. But there seems no reason to suppose that these variables are greater when casting large ingots than when casting small ingots; it might be supposed that both the area and period of contact would be less the larger the ingot cast. If the opinion that larger ingots contain more non-metallics is prevalent, might it not be due to the fact that the non-metallics coalesce into larger globules in larger ingots because they have more chances of doing so? Because the globules are larger they are more easily visible, but the gross amount of them is not, therefore, greater.

So far as one may judge from a small photographic reproduction of the sulphur prints taken from the sectioned ingot, the 20-ton block of steel is remarkably free from segregates, and it might, I believe, be

made still better in this respect by small modifications in the casting process. The lines of segregates visible near the top corners in Fig. 5 (Plate XXVI.) appear to be due to the growth of crystals horizontally from the sides of the mould. If this growth can be prevented, as it might be, by keeping the edges of the upper surface fluid and leaving the centre of the upper surface to take care of itself, then the line segregates will be minimised, or may even be practically absent. The obvious ideal would be a block whose upper surface contained the mass segregates, and that ideal does not appear to be too Utopian.

In addition to its presentation of interesting facts, the paper provokes speculation. At what speed ought such an ingot to be cast? My first impression is that a high rate of casting would be advisable, perhaps the higher the better up to any extreme which could be reached by a ladle nozzle of fantastic size. The behaviour of the bottom plate might impose limitations in this respect; and, indeed, the condition of the bottom plate after repeated use may be one of the graver concerns of this method of ingot-making. The bottom plate might usefully be provided with the usual splash-pot, but it should be free from widely spaced cavities or the ingot may suffer from vertical cracks.

No person associated with the production of large ingots and forgings can fail to be interested in the paper; nor can there be two opinions, in the minds of unprejudiced persons, about the promising nature of the Parsons-Duncan experiment. But it is not unreasonable to inquire how the essentials of the process are likely to withstand the wear and tear associated with a casting pit. It is more than likely that difficulties will crop up before the twentieth or the fiftieth large ingot has been made, and it is to be hoped that after the hundredth large ingot has been made the authors will lay before the Institute their accumulated experience and wisdom.

Professor H. C. H. CARPENTER, F.R.S. (Hon. Treasurer), wrote: The method adopted by the authors for the production of sound steel is an extremely interesting one. Although the paper contains an account of what is really only one experiment, a considerable measure of success has been achieved. The further information given at the presentation of the paper as to the second experiment, in which a different method of heating the top of the ingot was described, is an important further development in the direction of success.

The authors' insistence that the heterogeneity of a steel ingot is only partially disclosed by the ordinary methods of chemical analysis, since the drillings always contain purer metal which dilutes the segregate, is thoroughly justified. The method of sulphur printing, which has been fully developed by them, undoubtedly gives a truer indication of the position and extent of the segregates.

There is one aspect of the influence of the presence of non-metallic impurities in steel which is neither referred to in the paper, nor was it mentioned in the verbal discussion, and this point should be

emphasised. These impurities act in two distinct ways in causing a deterioration of the properties of steel: (1) They themselves constitute centres of weakness and really act as voids in the steel; (2) they cause a decarburisation of the steel in their neighbourhood and thus weaken the metal. I have myself examined a large rotor which had failed in practice, and found that *in certain parts the steel had been completely decarburised by the non-metallic inclusions present*. It had been converted into what may be regarded as low-grade iron. The fracture of the rotor took place preferentially through these areas, which is not in the least surprising, since they constituted the weakest part of the metal of which it was composed. The harmful effect of non-metallic impurities, therefore, is a double one—namely, both physical and chemical.

In conclusion, I should like to emphasise the point that this paper provides another illustration of the fact that knowledge gained in one industry can often be applied with great advantage in another industry.

Mr. E. HOUBAER (Seraing, Belgium) wrote: Sir Charles Parsons' process is of special interest. All persons who have had to deal with the forging of large ingots have experienced disagreeable surprises due to segregation, such as dark streaks and "ghosts" visible in the polished parts, &c., which have resulted from time to time in the scrapping of forgings. The Committee on the Heterogeneity of Steel Ingots, as a result of their researches, came to the conclusion that segregation was unavoidable. The art of the forgerman consists therefore in so making use of his ingot that the properties of the finished forging are not injured by segregation.

Sir Charles Parsons' researches, guided by a peculiar spirit of observation, remarkable in that it resolutely leaves on one side the routine followed in the past, conclude precisely as to the possibility of casting large masses of steel without central segregation, but in so doing sacrifice certain facilities of working, important from the forgerman's point of view. The lengthened form of the ingots in general use is imposed by conditions of handiness in working. It is no rarity for the forgerman to insist on a holding tail being tacked on to the ingot. The new process takes no account of these forging facilities and upsets accepted methods.

If, however, we remember the extreme importance of avoiding as far as possible all heterogeneity in large forgings, it is evident we must not hesitate to sacrifice convenience in forging to quality in the material, and consequently all processes which may give us increased homogeneity of metal deserve our attention and should be made the subject of practical trial.

Mr. J. N. KILBY (Sheffield) wrote that the most important feature of the work was the adoption of a specially shaped mould producing an ingot differing greatly in its dimensions from general practice,

though the principles were not contrary to already known facts. The influence of mould dimension upon pipe and segregate was too well known to discuss; suffice it to say, the shorter the ingot and the greater its proportional cross-sectional measurement, the less acute the V shape of the defective region. It would have been surprising had the authors not obtained from their squat ingot a less pronounced V-shaped zone than would be the case where tall moulds were used.

In an endeavour to gauge the value of the proposed method of casting steel and the principles advocated, it must first be remembered that the experiment was based upon a mass of metal which was almost akin to a steel casting. Further, the conditions laid down by the authors for preheating the mould to a high temperature and for the subsequent prolonged heating of the cast ingot had, along with properties of the refractory lining, certain influences upon the mechanical tests shown—that was to say, on the ingot—but it did not follow that such ingot tests lived to the forging. The tests given were not vastly different from those expected from a steel casting of the dimensions and analysis given.

The authors' contentions regarding the failings of chill ingot moulds were hardly sound, until chill ingots, similarly shaped to the one they had used, were experimented upon and failed, and also where suitably shaped feeder-heads were used on such chill ingots.

A refractory-lined composition mould of the same dimensions would give almost similar results without greatly preheating the mould, or heating subsequent to casting; the authors' results bore out what was known concerning the properties of composition-cast ingots, which had been in general use years ago for heavy ingots.

To revert to the special ingot, the authors admitted that the analyses of the samples taken from the varying positions of the section cut from the centre of the ingot did not confirm the sulphur and other prints, and they assumed that the analyses obtained were of secondary importance. He did not agree with their view, the more so as they said that if judged on analysis alone their ingot only compared with general practice. The variations shown were sufficiently great to give much food for thought, and if the segregate zone were traced from those figures it would be seen to assume a V shape. The figures varied between:

Carbon	0.22 to 0.31%
Sulphur	0.039 „ 0.050%
Phosphorus	0.047 „ 0.061%

The authors might not look upon those variations as serious, but there was no doubt that for any high-grade forging they would be fatal. He had had much experience recently with special forgings, of analysis and physical properties similar to those given in the paper, on which central transverse tests of the most searching character were taken. Those forgings were made from chill ingots with ample width and quality of feeder-head. Most of the transverse tensile test-pieces

were in the range 28 to 32 tons breaking strength and 28 to 34 per cent. elongation, coupled with good elastic limits and reductions of area.

The maximum sulphur and phosphorus contents were 0·035 per cent., and check analyses were taken from a central position near the top of the forging. The forging would have been rejected for slight segregate, say, 0·039 per cent., or low elongation; most certainly the authors' ingot would have failed on analysis alone, unless at least 30 per cent. were taken from the top of the ingot.

He asked what discard the authors proposed to cut from the top of the ingot, and what weight of steel they would cast on to the ingot for engaging the porter bar. Little was said about the base discard, so he presumed the authors believed it would be slight. He thought they should be prepared for a considerable loss in that direction; faster teeming might help a little, but that did not abolish the necessity for a bottom discard.

The authors said nothing about the possible fluxing of their mould lining into the outer inches of the ingot. Undoubtedly a certain proportion would be eroded by the heat and action of the steel, and become admixed. Would they say how they would repair such cutting as would take place after making a few ingots in the same mould, and how they would prevent any of the material which they might use from dropping into the steel during casting? In aiming at a better ingot, the outer inches should not be forgotten; they were as important as the inner portion, both as regards strength of the product and freedom from non-metallic matter.

Dr. H. MOORE, O.B.E. (Research Department, Woolwich), wrote that Professor Andrew's reference to segregation of carbon had led him to include a series of carbon estimations in his examination of material from the 20-ton ingot described in the paper. A radial slice of the ingot had previously been placed at his disposal through the kindness of Sir Charles Parsons, Mr. T. M. Service, and the Committee on the Heterogeneity of Steel Ingots. A strip, $\frac{3}{4}$ in. wide and parallel to the vertical axis of the ingot, was cut at a position 21 in. from the axis and thus near the position half-way between the axis and the outside surface. Shapings were taken from this strip, each sample being taken over a vertical length of 0·5 in. and a thickness of 0·3 in. Carbon was estimated in duplicate in each sample, very close agreement of the duplicates being obtained throughout. The results were as follows:

Distance from Bottom of Ingot. In.	Carbon. %	Distance from Bottom of Ingot. In.	Carbon. %
0-0·5	0·24	3·5-4·0	0·26
0·5-1·0	0·235	4·5-5·0	0·245
1·0-1·5	0·235	5·5-6·0	0·24
1·5-2·0	0·24	8·5-9·0	0·23
2·0-2·5	0·255	11·5-12·0	0·255
2·5-3·0	0·255	14·5-15·0	0·255

These figures gave no support to the suggestion that "at the bottom of the ingot the whole mass was almost pure ferrite." They pointed, indeed, to a remarkable uniformity of carbon content over a distance of 15 in., measured in the direction of solidification and of crystal growth, from the bottom surface at which solidification began. The strip had been examined microscopically throughout its length; the indications of its structure agreed with those of the analyses. So far as they went, these results suggested that the slow uni-directional freezing sought in the authors' process of casting ingots was no more likely to produce excessive carbon segregation than the methods in general use.

He (Dr. Moore) had regarded the ingot described in the paper as an extremely interesting experiment rather than an example of a practical method of manufacture. He had shared the doubts expressed by Dr. Hatfield and others as to the practical utility of the process. For hollow forgings of the type in which he (Dr. Moore) was specially interested, the axis of the ingot, which was removed in the course of the further operations, was probably the least objectionable location of unavoidable segregation and unsoundness. He had, however, been much impressed by the arguments and additional information put forward by Mr. Duncan, and he looked forward with the greatest interest to the further trials of the authors' process.

The AUTHORS wrote thanking all those who had taken part in the discussion at London, Glasgow, and Sheffield, and for the valuable criticism and encouragement which had been given, and saying how gratified they were at the interest taken in their method.

Mr. Service, in speaking about non-metallic inclusions in the authors' ingot, said: "It might be supposed that owing to the long time the ingot took to become solid—14 hr.—a certain proportion of those inclusions would rise to the surface, but that did not appear to occur to any great extent. (See Figs. 10 and 12, Plate XXX.; Figs. 16 and 17, Plate XXXI.; and Fig. 21, Plate XXXIV.)." Figs. 10 and 12 were taken from the segregated zone at the top of the ingot, and Figs. 16, 17, and 21 from scum lines, which the authors considered were trapped in the ingot owing to the very slow speed of pouring. No evidence had been produced up to the present as to the quantity of non-metallics in the new ingot, but Mr. Howarth had kindly promised to investigate that point. Until evidence was forthcoming to the contrary, the authors considered it reasonable to expect that the amount of non-metallics should be less, since the cooling proceeded slowly from the bottom upwards, thus enabling the particles to coalesce and rise to the surface by virtue of their lower specific gravity.

Dr. Rosenhain had asked, "What was the justification for the scientific idea at the base of the experiment, that an ingot, in order to be satisfactory, should be solidified from the bottom upwards?" He further said that "perhaps the idea at the back of the authors'

minds was that the junctions of crystals were in themselves sources of weakness," and further pointed out that "such an idea was inherently a fallacy." While thanking Dr. Rosenhain, the authors wished to disclaim all responsibility for such an idea.

As stated on p. 256, the authors' method of overcoming segregation and axial unsoundness was based on the principle that the freezing of the ingot should proceed from the bottom upwards, the isothermals being substantially parallel to the bottom of the ingot, and it was thought that the growing crystals would push the less pure liquid containing the segregates in front of them, so that they would eventually reach the surface of the ingot instead of being trapped and forming the Λ -segregates, as found in the ordinary ingot; as Mr. Brearley wrote in his contribution, "An obvious ideal would be a block whose upper surface contained a mass of segregates, and that ideal does not appear to be too Utopian."

The authors noted that Dr. Rosenhain did not think the changes in the distribution of segregates which they had obtained by their method were really so very striking, and they assumed that he based that conclusion on an examination of the analyses obtained from different parts of the ingot. They would suggest that a truer indication of the distribution of the segregates would be obtained by an examination of the sulphur print, Fig. 5 (Plate XXVI.), which showed to anyone familiar with the appearance of sections cut from large masses of steel a very striking change in the distribution of the segregates. The authors were quite familiar with the successful work on the elimination of gas from solidifying metal which had been carried out in the laboratory with which Dr. Rosenhain was connected, and had experimented with that method in their own foundry. The authors agreed with Dr. Rosenhain that the new method of casting steel would certainly tend towards the elimination of gas, but they could not agree that that mainly accounted for the striking mechanical tests obtained from the centres of discs forged from an ingot made by their method. If the slow cooling produced a very coarse crystal structure, which Dr. Rosenhain thought was perhaps in many respects its most serious disadvantage, how did he account for the excellent mechanical properties of the forged ingot, bearing in mind that those tests were taken in three directions?

With regard to the other disadvantage mentioned by Dr. Rosenhain—namely, the formation of a crust on the surface of the metal as it rose in the mould—the authors considered that that was due to the mould being filled at too slow a rate; as stated on p. 262, "A 3-ton ingot, 3 ft. in diam., cast with the same size nozzle, namely, $1\frac{1}{2}$ in. in diam., was found to be entirely free from these defects," and, furthermore, the difficulty of securing a steady rise of crust on ingots cast by the authors' method should be no greater than when casting ingots in the ordinary way, as many of those ingots were as large in diameter as the authors' ingot.

They were interested in Dr. Rosenhain's alternative method of

obtaining sound steel, but they thought that the practical difficulties which would be encountered in carrying out his method were very much greater than in the method proposed by them, since, after casting five 20-ton ingots by their method, they had found that there were no practical difficulties whatever.

The authors thanked Mr. McDonald for his comments regarding the white lines or bands shown on the sulphur print, Fig. 5. There had been a certain amount of misunderstanding regarding those white bands, and the authors wished to state definitely that the non-metallic inclusions referred to in the paper and in the discussion at London were not found in the white bands, but only in the dark lines, which the authors considered to be scum lines.

With regard to Mr. Hamilton's difficulty concerning the discard of the segregate at the top of the ingot, it must be remembered that the discard would only be cut off after the ingot had been forged, in which case the process would be similar to that in use at the present time, where, after the ingot was forged, a certain percentage was cut off from the top and bottom.

The authors thanked Mr. Saniter for banishing Dr. Hatfield's fears concerning the danger of sand or dirt getting into an ingot from the brick lining of the mould. They were glad to note that he considered the authors' method might help in carrying the non-metallic inclusions to the top, and they would ask him to keep an open mind on that question until Mr. Howarth had completed his examination and proved whether there were more non-metallic inclusions, or less, in the authors' ingot.

The authors thanked Mr. Munro for his kind remarks, and noted that in large hollow forgings a 21- to 27-in. core was removed. They agreed that that would remove all the central weakness, but could not agree that the secondary segregation which was left in the walls of the forging was not affected by any of the processes for which the final forging was used, though that was probably so in the case of the special forgings which Mr. Munro had in mind. They quite agreed that it was doubtful if there were a press in Great Britain which could forge an ingot 16 ft. in diam., though no doubt if the demand arose for such ingots the presses would be forthcoming. They were available in Continental steelworks. The authors thought that the bar would have to be sunk about 15 in. to ensure the handling of the ingot with safety, and they agreed that that would affect the amount of discard, but probably one would be quite satisfied to obtain a sound ingot with such a small discard.

With regard to forging a short large-diameter ingot, the authors considered there was a definite relationship between the diameter and length of the ingot and the size of the press, and if that relationship were observed, no difficulty would be experienced during forging.

They were pleased to note that Mr. Munro considered their type of ingot would be suitable for small hollow forgings, and that he would be prepared to accept forgings which otherwise met his specifications.

The authors thanked Mr. Russell for his remarks, and noted that he agreed that the authors' was the ideal method. With regard to Dr. Oertel's experiments, they thought that steel-makers would hesitate to cast 20-ton ingots in water-cooled moulds, and while they agreed that very good results would be obtained if the whole ingot could be made to solidify instantaneously, they did not think that an ingot of large cross-section, cast in a water-cooled mould, would be free from segregation, since it would not be possible to prevent differential freezing of the centre.

The authors thanked Mr. Howarth for his promise to examine sections taken from their ingot for non-metallic inclusions; they would await his report with great interest. They assured him that there were no blowholes in the bottom of the ingot, and nothing which would necessitate a large discard from that end of the ingot.

The authors thanked Professor Desch, and wished to state once more that the horizontal white lines did not contain an unusually large proportion of non-metallic inclusions. They could assure him that their method of casting steel did not bring with it a liability to greater internal stress, and to anyone familiar with the casting of large ingots, the tear which occurred in the first ingot was readily understandable.

The authors thanked Professor Benedicks and Mr. Löfquist for their interesting contribution, and desired to say that they did not adopt the reversed cone type because of the difficulty of stripping; they thought that if the heating of the top was properly carried out, casting the big end up would not be necessary. They noted that Professor Benedicks referred to the occurrence of the well-marked transverse bands; if he was referring to the white bands shown in Fig. 5, it was not correct to say that they contained oxides, though they were certainly lower in carbon, sulphur, and phosphorus. The bands containing oxides were well illustrated in Fig. 8 at position *F* (see Fig. 7), and an examination of them in the ingot would, the authors felt satisfied, leave no doubt that they were scum lines; they were entirely absent in the 3-ton ingot, which was poured at a proportionately much faster rate. They noticed that very soon after pouring commenced, the mould was filled with gases escaping from the steel, which made their escape through the holes in the cover, and they considered the remainder of the pouring was conducted in a reducing atmosphere provided by the escaping gases. They agreed that those oxide particles would give rise to a reduction of the carbon and account for the presence of surrounding ferrite.

They thanked Mr. Brearley for his very interesting contribution. They considered that the absence of jog or kink in the load-extension diagrams in Fig. 3 was a proof that the material was in a state of strain; the curves were similar to those which would be obtained from a piece of cold-worked steel. Further proof of that was shown by Professor Andrew in his Figs. K, L, and M, where the ferrite and pearlite were considerably distorted. They thought that Mr. Brearley's

explanation of the greater ductility of the test-pieces taken from the bottom of the ingot was probably correct. They also agreed with Mr. Brearley that the statement on p. 262, to the effect that the amount of non-metallic inclusions was usually greater in larger ingots, required reconsidering, and they accepted his explanation that the amount of non-metallic inclusions was usually the same, whatever the size of ingot. They agreed that the heat should be concentrated on the edges of the upper surface, leaving the centre of the upper surface to take care of itself, and that was done in the second 20-ton ingot cast by the authors' method. They were also in agreement with him that a high rate of casting would be advisable. With regard to the condition of the bottom plate after casting, that was quite easily renewed, as it was only in the nature of a protective plate for the large chill block of metal underneath. The authors would certainly lay before the Institute their experience after the hundredth large ingot had been cast.

The authors thanked Professor Carpenter for his interesting contribution, and for emphasising in two distinct ways the action of non-metallic impurities in causing the deterioration of the properties of steel.

They welcomed the contribution of Mr. Houbaer, and could confirm his experience with segregation in large forgings. Mr. Houbaer would note that in the second ingot cast by the authors' method the holding tail was tacked on to the ingot to give increased facility in forging. They were pleased to note that Mr. Houbaer realised the extreme importance of avoiding as far as possible all heterogeneity in large forgings, and considered the authors' method worthy of attention and a practical trial.

The authors thanked Mr. Kilby for his contribution, and gathered that he considered that the failings of chilled ingot moulds might disappear if they were similarly shaped to the one the authors had used; although that was possible, the authors did not think it was probable, on account of the chilling which would take place from the sides of the mould. They also noted that he considered preheating the mould and heating subsequent to casting were unnecessary, and from their experience with the 3-ton ingot they were inclined to agree that it was not necessary greatly to preheat the mould; but they thought that radiation from the top, especially at the sides, must be prevented, otherwise crystal growth would take place at the top and trap the segregates in the central portion. Mr. Kilby was not correct in stating that the authors assumed that the analyses obtained were of secondary importance; they said that in their opinion sulphur-printing gave a truer indication of the harmful segregates than analysis, and they noted that Professor Carpenter and Mr. Brearley confirmed that view. An examination of the results obtained across the segregate (Table II.) would make it clear why the authors considered segregates harmful. It should be stated that the segregate referred to in Table II. ran approximately parallel to the shape of the finished

forging, and was located between the central axis and the outside at a distance of about 9 in. from the outside of the forging at its largest diameter. Mr. Kilby stated that the variations found in the authors' ingot would be fatal for any high-grade forgings, but if he would refer to the First Report of the Heterogeneity Committee, he would find that similar variations in analyses were present in all the ingots examined, and those ingots represented the highest grades which could be obtained. The authors thought that when he wrote his contribution Mr. Kilby was probably not aware of the excellent mechanical tests which had been obtained from discs forged from a 20-ton ingot cast by their method, and, speaking from many years' experience of similar tests from discs cast by the ordinary method, the authors could assure him that the tests obtained from their ingot were very much better than could be obtained from discs forged from steel cast in the ordinary way. With regard to the amount of discard from the top of the ingot, the authors would remind Mr. Kilby that in the manufacture of turbine forgings many steel-makers used only 50 per cent. of the ingot, and the forging still contained axial weakness and the Λ -segregates. With regard to the bottom discard, they referred him to the very thorough examination to which a portion of that had been subjected by Dr. Moore, concerning which he referred to the remarkable uniformity of the carbon content for a distance of 15 in. from the bottom surface upwards. The authors would not expect any greater fluxing of their mould lining than took place in the ordinary ladle, and such erosion as did take place would be repaired in the same way as the ordinary ladle was repaired. They could assure him that they were not forgetting the outer inches, and so far these had been entirely satisfactory.

The authors were much obliged to Dr. Moore for his very thorough examination of a vertical strip, $\frac{3}{4}$ in. wide, extending from the bottom of the ingot upwards to a distance of 15 in., and noted that a microscopical examination of that strip confirmed the analyses which he had obtained, and indicated a remarkable uniformity of carbon content over that area. They wished to assure Dr. Moore that as the result of having cast five ingots by their method, they considered it to be decidedly a practical method of manufacture, and they would draw his attention to the fact that, although in hollow forgings of the type in which he was specially interested the axis of the ingot was removed, there still remained the Λ -segregates, which were areas lacking in ductility, as indicated by the mechanical tests in Table II.

The authors would be pleased to grant facilities to all those interested, to examine the sectioned ingot or the casting and forging of further ingots.

In conclusion, the authors wished to direct attention to Mr. Service's contribution to the discussion, as they considered that he stated, in the fewest possible words, the existing drawbacks of large forgings and the extent to which he considered the authors' method overcame them.

THIRD REPORT ON THE HETEROGENEITY OF STEEL INGOTS.

BY A COMMITTEE OF THE IRON AND STEEL INSTITUTE.

SECTION I.—INTRODUCTION.

THE work of the Committee on the Heterogeneity of Steel Ingots is continuing without intermission, and this, its Third Report, is now presented to the Institute.

The First Report ¹ was exploratory in character, and dealt with the nature and manner of the heterogeneity disclosed in the examination of sixteen carbon steel ingots of the solid type, the weights ranging from $14\frac{3}{4}$ cwt. to 172 tons. A general discussion of the data was presented, and tentative explanations of the phenomena observed were recorded.

The Second Report ² contained the results of the examination of seven alloy steel ingots of weights ranging from 15 cwt. to 119 tons, and of nine carbon steel ingots of types differing from those dealt with in the earlier Report. The subject of the design of ingot moulds was also considered, and a tentative analysis of the considerations governing mould design was put forward.

Several interesting further investigations undertaken by the Committee are in hand, and the results will be given in subsequent Reports. This, the Third Report of the Committee, however, is different in character from the preceding ones. Whereas the earlier Reports were records of the collective work of the members of the Committee and statements of collective views, the present Report consists of sections devoted to researches into fundamental matters. As recorded in the previous Reports, the Committee was able, through the financial resources of the Iron and Steel Institute, to invite competent investigators to work upon some of the questions requiring elucidation. Some of

¹ *Journal of the Iron and Steel Institute*, 1926, No. I. p. 39.

² *Ibid.*, 1928, No. I. p. 401.

the work undertaken in this way has reached a stage at which it may suitably be reported to the Institute. The investigators are solely responsible for the accounts of their work, which form the following sections of the present Report, and for the deductions they have drawn. The Committee hopes subsequently to make use of the data which are thus being gradually accumulated, interpreting the experimental results as its discussions may determine, but considers it important in the first place to put forward the individual reports and views of the investigators themselves.

This present Report consists of :

SECTION I.—Introduction.

SECTION II.—“The Liquidus and Solidus Ranges of Some Commercial Steels,” by J. H. Andrew, D.Sc., and David Binnie, B.Sc., Ph.D., A.R.T.C.

SECTION III.—“The Solubility of Iron and Manganese Sulphides in Steel,” by J. H. Andrew, D.Sc., and David Binnie, B.Sc., Ph.D., A.R.T.C.

SECTION IV.—“Interim Report on the Density of Molten Steel,” by C. H. Desch, F.R.S., and B. S. Smith, M.Met.

SECTION V.—“The Effect of Latent Heat on the Solidification of Steel Ingots,” by N. M. H. Lightfoot, M.A.

In Section II. will be found the Report by Professor Andrew and Dr. Binnie on the liquidus and solidus ranges of some commercial steels. These steels, covering a wide range of carbon and alloy steels, were supplied by members of the Committee, together with the analyses. The analyses were then carefully checked under Dr. Moore's supervision at the Research Department, Woolwich. It will be seen that the selection of steels was such that the data had immediate application to the problems under consideration by the Committee. The number of steels is being extended still further, and it is hoped that this investigation will finally cover most of the industrial steels. The object of the authors was to determine the temperatures at which freezing commenced and finished in steels of these various compositions. As pointed out in the earlier Reports, knowledge of the range of temperature over which the freezing takes place is

of fundamental importance, not only as regards the light which it throws upon the production of heterogeneity and the provision of optimum casting temperatures, but also because of its value in assisting in determining the upper limit of temperatures which may be attained in reheating steel for hot-work, since such data enable limiting values for working temperatures to be set well below those at which partial fusion of the steel takes place. Professor Andrew and Dr. Binnie have approached the subject experimentally, in a manner which is technically satisfactory from the point of view of the use of thermal data for the purpose in mind. The temperature of the commencement of freezing of each steel studied is clearly indicated, whilst the authors also claim to mark out the whole range of temperature during which the differential freezing effect takes place. Their experimental methods are described, and the authors make interesting deductions concerning the effect of composition, and also concerning the application of the data they have obtained to the problem of ingot manufacture.

In Section III. will be found an interesting treatment of the problem of the solubility of iron and manganese sulphides in steel, also by Professor Andrew and Dr. Binnie. This subject the Committee realises to be an extremely difficult one for experimental treatment. The report of the work will, no doubt, be read with much interest by those who are studying this subject. The method of attack consisted of melting pure iron with sulphur, manganese being added as manganese metal when required. The alloys produced were studied by the thermal method and also by the microscope. It is realised both by the investigators and by the Committee that the work is necessarily more or less of a qualitative type, but it is, undoubtedly, a valuable contribution to this subject.

Section IV. is a report by Professor Desch and Mr. Smith upon the interesting problem which they undertook to deal with—namely, the changes in density occurring in steel in the neighbourhood of the freezing point. It will be clear from a survey of this section that the authors are dealing with a problem of great experimental difficulty. The Committee feels that an account of their apparatus and methods will be of value to investigators in this field. The data so far obtained should only

be looked upon as preliminary values, since the work is being carried forward with a view to improving the refinement of the experimental methods. The Committee regards the final determination of the density of steels in this range of temperature as being of the most fundamental importance when considering the mechanism of freezing.

In Section V. the Committee presents a study by Mr. Lightfoot, in which, by mathematical treatment, he has endeavoured to give some indication of the effect of latent heat on the solidification of steel ingots. The subject of freezing has been treated by previous theoretical investigators, but the effect of latent heat has not hitherto been treated on precisely the same lines. It will be seen from a study of Mr. Lightfoot's contribution that three hypothetical cases have been considered, which help one, in the first place, to visualise the progress of the rate of freezing at the outer wall, and, secondly, to obtain an idea of the conditions that apply towards the latter stages of freezing at the centre of the ingot.

Whilst mention is being made of this last section, the Committee would like to take the opportunity of emphasising the importance of mathematical analysis in regard to the study of ingot production. There are so many aspects of the matter which will remain extremely difficult to deal with experimentally, but on which much light can be thrown in this manner. For instance, a study might be made of the separation of the ingot from the wall of the mould, since this is clearly a function of the strength of the initial freezing shell to resist the internal pressure. An endeavour might be made to approach this subject from the angle of the mechanical and physical properties of the shell and the actual stress imposed by the liquid metal at the critical moment. The effect of the separation of the ingot from the wall of the mould has previously been postulated by the Committee as a point deserving serious consideration, and, incidentally, it will be clear that the separation, occurring along the length of the ingot at different times, probably has its effect upon the manner of freezing. The Committee has in mind numerous other cases of a similar nature which it is proposed to investigate by this method of attack.

In presenting this Report, the Committee would like to take

this opportunity of thanking the authors for their reports, and also the Council of the Iron and Steel Institute for the substantial financial assistance which has permitted the experimental work to be carried out.

It is much to be desired that the four several sections of the Report should receive full discussion on presentation, since it is felt that the investigators engaged upon such fundamental problems should have the full advantage of the views of everyone interested.

SECTION II.—THE LIQUIDUS AND SOLIDUS RANGES OF SOME COMMERCIAL STEELS.

By Professor J. H. ANDREW, D.Sc., and DAVID BINNIE, B.Sc.,
Ph.D., A.R.T.C. (Carnegie Scholar) (Glasgow).

Introduction.

THE freezing ranges of the iron-carbon system have been determined completely by Carpenter and Keeling,¹ and partly by Ruer and Klesper,² whilst the solidus has been further investigated by Japanese workers.³

The methods employed for determining the solidus have been micro-analysis of quenched specimens, variation in electrical resistance on passing through the solidus, and magnetic analysis. So far as the authors are aware, in no case has the thermal method been used to detect the solidus.

An experimental measurement of the liquidus of the iron-carbon system is a comparatively simple matter. All that is necessary is to melt the sample, insert a thermocouple in the molten material, which allows of a time-temperature record to be made, and finally to analyse the sample when cold.

The difficulty of carrying out measurements upon steels of predetermined analysis lies in the fact that a variation of the carbon content, usually a loss, is almost certain to occur, whether the melting be done in air or *in vacuo*. The effect of this loss of

¹ *Journal of the Iron and Steel Institute*, 1904, No. I. p. 224.

² *Ferrum*, 1913-14, vol. xi. p. 257.

³ S. Kaya, *Science Reports of the Tôhoku Imperial University*, 1925, vol. xiv. p. 529; K. Honda and H. Endô, *ibid.*, 1927, vol. xvi. p. 235.

carbon greatly militates against the value of the results, for as it is not definitely known at what period of heating or melting the loss may have taken place, it cannot, therefore, be concluded that the freezing-point value obtained is representative of the composition revealed by the analysis of the melted material.

Method of Investigation.

At the outset, three main problems presented themselves : (1) Type and design of furnace to be employed ; (2) metals or

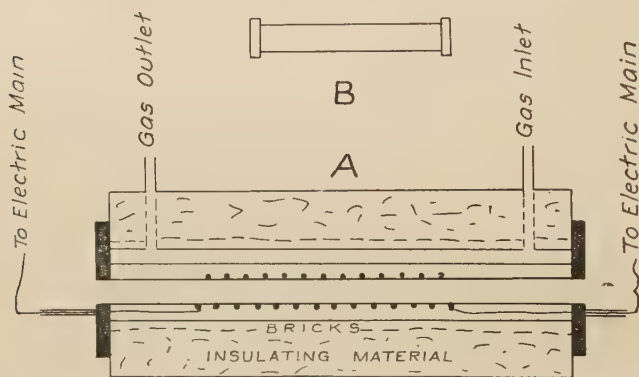


FIG. 1.

alloys to be used as thermocouples ; and (3) method of measuring the change in phases with temperature.

Type of Furnace.—In view of the high temperatures involved, and having regard to the facilities available, it was decided to use a molybdenum wire-wound furnace. On account of the greater uniformity of heating in a horizontal, as compared with a vertical type of furnace, the former was decided upon, and one was designed and constructed in the Department (see Fig. 1, A).

A molybdenum furnace requires a reducing or neutral atmosphere surrounding the heated wire ; this was provided for by cracking ammonia. The cracking train consisted of a large flask for boiling ammonia (sp. gr., 0·880), and five cracking tubes of Morganite material connected in series, all filled with iron turnings and heated to a temperature of 600° C. by means of a nichrome-

wound furnace in which they were encased. Between the boiling flask and the cracking tubes was placed a mercury seal which acted as a safety trap, as may be seen in Fig. 2, which illustrates the whole apparatus. The mixed gases were then led through a special form of wash-bottle, shown in Fig. 3, designed to supply a continuous stream of fresh water for washing the gas, in order to remove as far as possible any undecomposed ammonia carried over with the gas stream. The gas was then dried by passing it through bubblers containing sulphuric acid, and towers containing calcium chloride; thence it was led to the furnace.

In the first instance, the heat insulator used for the molybdenum furnace was kieselguhr, but this was found to slag badly with the alundum tube forming the outer jacket of the annular space, which was necessary in order to be able to maintain a hydrogen and nitrogen atmosphere around the winding. Eventually, a thick layer of ground alundum (obtained by grinding up old tubes previously used in the furnace) was placed immediately around the sleeve tube, and the remaining space was filled up with coarsely ground Silacine, kindly presented by Professor Campion. The refractory tubes used throughout were made by coating an iron former, on which were wrapped two or three layers of brown paper, with a moistened alundum mixture, consisting of 90 per cent. of coarse grade and 10 per cent. of fine grade. After drying and roughly filing to shape, the tubes were heated with the former to 400° C., in order to burn the paper, and so permit the removal of the tube from its former. After rubbing down to shape with sand-paper, the tube was finally baked at 1000° C. The tubes made in this manner proved to be excellent in every way, with respect to both the absence of cracking and to their ability to withstand the highest temperatures employed.

Prior to starting a run of the furnace, a copious flow of gas was allowed to pass through for about half an hour, in order to expel all air. This supply could be cut down considerably during running and during the period of cooling.

The direct current for operating the furnace was taken from the 250-v. mains, 17 amp. being sufficient to maintain the furnace at a temperature of 1550° C. About 2 hr. were required to heat the furnace from cold to 1500° C. For the purpose

- I. Reservoir for Constant supply of Water
 II. Flask containing Ammonia Sp. Gr. 0.880
 III. Mercury Safety Valve
 IV. Wash-Bottle with small quantity of Sp. Gr. 0.880 Ammonia
 V. Electric furnace with Five Tubes for Cracking Ammonia
 VI. Two Bottles, Empty
 VII. Special design Wash-Bottle
 VIII. Three Concentrated Sulphuric Acid Wash-Bottles
 IX. Calcium Chloride Drying Towers

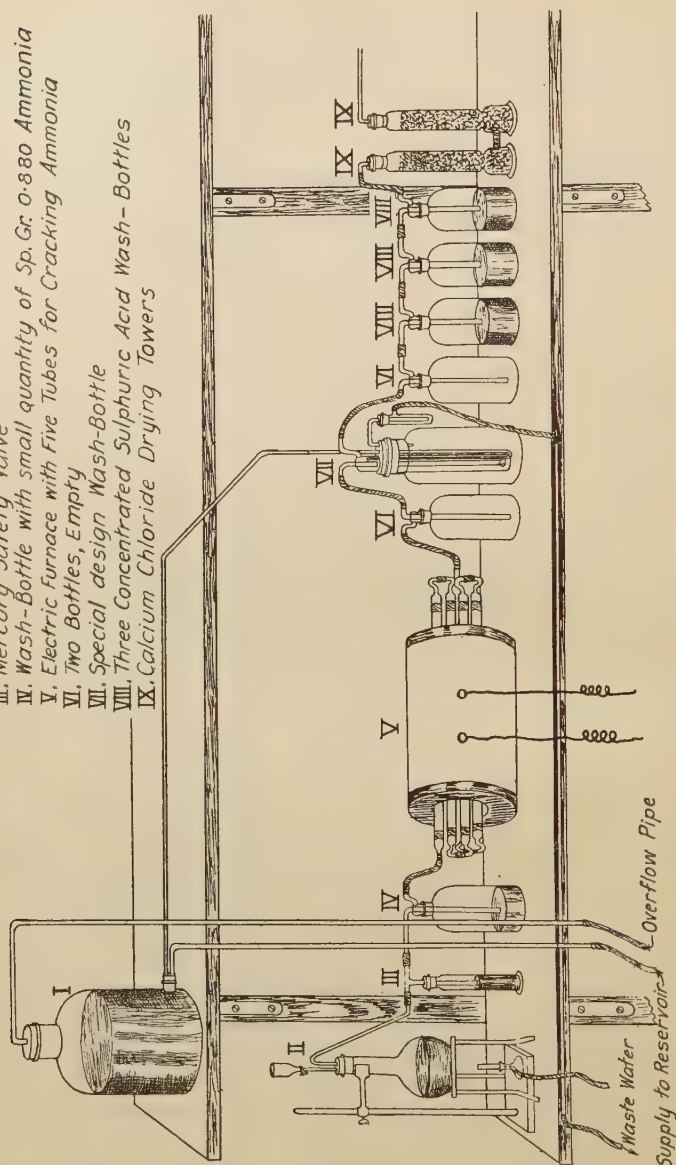


Fig. 2.

of obtaining a sufficiently slow rate of cooling when taking a freezing-point determination, a current of 10 amp. was allowed to flow in the circuit.

Thermocouple.—On account of the reducing atmosphere

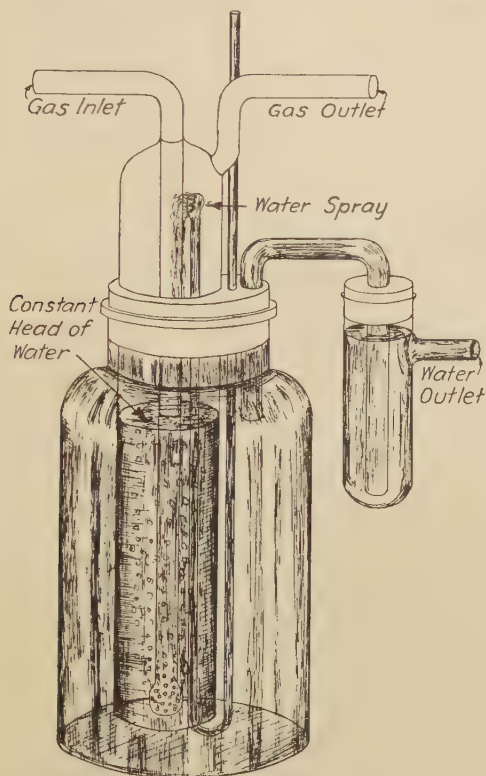


FIG. 3.

within the furnace, a platinum/platinum-alloy couple was out of the question. A couple made up of tungsten and molybdenum wires was found to be eminently satisfactory, and was used throughout the work. The tungsten and molybdenum wires purchased from the Tungsten Manufacturing Company were 0.4 mm. and 0.88 mm. in diam. respectively. A thicker tungsten wire than this was found to be too brittle. The thermo-junction was made by tightly twisting the molybdenum wire around the

tungsten wire. The e.m.f./temperature relationship conformed to a parabola, satisfying at all temperatures within which the couple was used the equation $Y = CX^2$. Calibration was effected by comparison with a platinum/platinum-rhodium couple for temperatures below 1200°C. , and from this section of the curve the equation was derived. This gave 1537°C. as the melting point of Armco iron (determined experimentally), the value proposed by Professor Carpenter. In all, three separate couples were used, and, whilst differing from one another with respect to their actual temperature/e.m.f. relations, they all conformed to the parabolic equation.

Method of Measuring Phase Changes. —In view of the prevalent assumption that thermal curves do not give a definite indication of the solidus, it was decided to employ electrical-resistance/temperature measurements. The procedure was as follows: The steel sample, in the form of a thin strip, was cut from the section provided; it was placed in an alundum boat about 10 cm. in length, 3 mm. in internal diam., and 4 mm. in depth. A hole was drilled in the centre of the specimen for the insertion of a thermocouple. The method of insulating the couple here adopted, and adhered to in the thermal measurements to be described later, was to thread the couple through a thin-walled capillary tube of transparent silica, the end at the centre of the specimen being luted up with alundum. In no case did the silica show signs at the end of a determination of having been fused. Holes were drilled at each end of the specimen for the insertion of the current leads, and two further holes, about 5 cm. apart and equidistant from the ends, for the p.d. connections. The current leads and p.d. wires were of bare tungsten; it was found that, provided these wires were at least 1 mm. in diam., they neither melted nor broke during a determination. The bare wires, moreover, ensured metallic contact with the steel, provided the boat was maintained in a horizontal position. In the first few experiments the metal tended to flow and sink in the boat, breaking contact with the wires, but this was overcome by luting every space between the specimen and the boat with alundum, and covering the whole with the same material. By this means the contour of the specimen was fixed, and determined entirely by that of the boat in which it lay. The fall in potential and

thermal e.m.f. were measured on separate Tinsley vernier potentiometers, each working in conjunction with a separate Tinsley galvanometer. The current was likewise measured by one of these instruments by working with a shunt.

On taking a temperature-resistance curve of Armco iron, as a means of trying out the method, two sources of trouble became evident. First, it was found that at temperatures above 1400°C . the thermocouple gave different readings, according to whether the current was passing through the furnace or not. Secondly, the length of the boat was greater than that of the zone of constant temperature within the furnace. The second difficulty was overcome by decreasing the length of the boat, and with it that of the specimen, but the changes in resistance registered by the shortened specimen as it passed through a phase change were so small as to make the method useless. The difficulty with the thermocouple was overcome by momentarily cutting off the current immediately before taking a reading of the p.d. system, but this was unsatisfactory, since the temperatures at which readings were taken were arbitrary, and could not be predetermined.

Upon taking a thermal curve of Armco iron with the current off, the time interval at the freezing temperature and at the δ - γ change was so large, due to the high sensitivity of the couple, that it was decided to rely upon thermal determinations as a method of investigation. The simplicity of this method as compared with the resistance method was marked. In the first place, only one potentiometer was necessary, and, secondly, instead of being beset with the difficulty of arranging for six separate wires to pass out of the furnace tube, and to insulate them from one another, with the thermal method but two wires were required.

The impossibility of obtaining a true temperature reading at temperatures above 1400°C . with the current flowing through the furnace, applied equally to the thermal and resistance method, and a very considerable time was taken in overcoming this difficulty. It was concluded, in the first instance, that electrical leakage from the furnace to the couple was the cause, alundum being known to conduct slightly at very high temperatures. To obviate this an inner tube of alundum was constructed, with flanged ends, as shown in Fig. 1, *B*; it was placed inside the

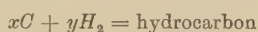
heating tube of the furnace, and it is clear that contact between the two tubes could only occur at the cold ends. The specimen for the thermal determination, measuring roughly $4 \times 1 \times 1$ cm., was completely encased in alundum and placed at the centre of this tube. This departure, however, had not the slightest effect, the thermocouple trouble being in no way mitigated. The only feasible explanation was that the cause of the trouble lay in the stream of thermions emitted by the molybdenum heating unit at the higher temperatures.

With this in view, the obvious method of attack was derived from a consideration of a thermionic valve, and consisted in placing a grid between the heating unit and the specimen. The grid as first constructed consisted of a short flanged tube, as shown in Fig. 1, *B*, around which were wound a few turns of molybdenum wire. The ends of this wire were earthed. The trouble, however, still persisted, and no improvement was obtained by charging the grid to various positive or negative potentials. After a large number of experiments had been performed, the trouble was eventually overcome by constructing the grid in the following manner: A tube similar to but shorter than that already described was prepared, and along its length were placed 8 lengths of molybdenum wire. These were bound at both ends by means of nichrome wire, and at the centre by one strand of molybdenum wire. The grid was completely insulated from all outside sources. At the high temperatures the grid was subjected to the thermions emanating from the molybdenum heating unit, and thus became charged to a definite potential. As the grid was insulated there could be no flow of current, but a back-e.m.f. was generated by the grid itself. Care was needed to see that no part of the grid came into contact with the conducting part of the tube, *i.e.* the heated portion. For this reason the grid was kept as short as possible to prevent sagging in the centre when it became heated. Eventually, it was found that if the flanged end of the grid lay in the heated zone, the other (cold) end could touch the furnace tube, provided that contact was made at a point beyond the winding of the heating unit. Further, it was found that to be effective the wires must lie along the tube; a coiled wire did not produce the desired result.

The grid deteriorated with use ; whilst a grid would usually last for as many as six or seven heats, in some cases a replacement was necessary after two or three heats. Any slight oxidation of the grid wire, caused by its removal from the furnace before it was sufficiently cool, destroyed its effectiveness, on account, it is thought, of the oxide acting as an insulator, and thereby decreasing its power of dealing with the thermions.

The grid constructed in this manner completely avoided all trouble from the heating circuit ; it made not the slightest difference to the temperature readings whether the current were flowing through the furnace or not.

Having overcome this difficulty (which would not have arisen had alternating current been available), an excellent melting and freezing curve of Armco iron was obtained. On experimenting with steels, it was found that, no matter what the original carbon content was, in every case curves similar in all respects to the Armco iron curve were obtained. A micro-examination showed a total absence of carbon in the remelted specimens. That hydrogen is an effective decarburiser is well known, but in view of the rapid dissociation of most hydrocarbon gases at high temperatures, whilst a slight loss of carbon was expected, its complete elimination was unexpected. It would thus appear that although the K value of the reaction



may be low, the rate of reaction from left to right must be extraordinarily rapid.

The possibility of the alundum crucible reacting with the carbon in the steel was suggested by the work of Jordan and Eckman.¹ Accordingly, alundum crucibles lined with shrunk magnesia, and bubbling the mixed hydrogen and nitrogen gas through volatile oils were tried, but the results were the same. As hydrogen seemed to be responsible for the decarburisation, nitrogen taken from a cylinder was tried. This was deoxidised by passing it through the same cracking train as was used for ammonia, only in this case the temperature was allowed to attain 1000° C. ; as a further precaution the purified gas was passed through two bottles containing pyrogallol, and thence through

¹ U.S. Bureau of Standards Scientific Paper No. 514, 1925.

the usual drying agents. Whilst the results showed some slight improvement, a considerable loss of carbon occurred, due, it was thought in this case, to water vapour. To correct this, two bottles containing phosphorus pentoxide were placed in the circuit, but with no improvement. Further, under these conditions the furnace windings gave way every two or three heats, and the alundum slagged badly with the insulating material. Arranging the furnace vertically, in order to be certain that no stagnant moisture existed around the specimen or the winding, was tried, but was of no avail.

After much experimenting, the difficulty was completely solved in the following manner: Crucibles of carborundum sand were moulded to shape by means of a wooden pattern; they were then dried, and baked. After grinding externally to size, they were lined with a thick coating of alundum, and again dried. The specimen, of roughly circular section, 4 cm. long and about 1 cm. in diam., containing a hole in the centre for the insertion of the thermocouple, was placed in the crucible. All spaces between the bottom and sides of the specimen and the crucible were filled in with alundum, and an alundum coating was placed over the top. Finally, the top was coated with carborundum. The quartz tube carrying the thermocouple was allowed to project just above the surface. As before, the end of the quartz capillary which made contact with the specimen was sealed by a thin coating of alundum. This device completely eliminated all trouble due to decarburisation, and steel specimens could be melted and remelted without any change in the carbon content.

Melting and Freezing Curves.

In Table I. are recorded the analyses of the steels used for melting-point determinations. In order to provide a basis for the comparison of the commercial steels, melting and freezing point determinations were made with Armco iron, and four crucible steels in which the impurities, with the exception of manganese, were low. The curves obtained with this series are given in Fig. 4, *A* to *E*, and the freezing and melting points are plotted in the diagram, Fig. 5. Since this diagram forms the basis for plotting the results of the commercial steels, it will be termed the "theoretical diagram."

TABLE I.—*Analyses of Steels used for Melting-Point Determinations.*

Analyses carried out by the Research Department, Woolwich.

Mark of Steel.	Carbon. %	Silicon. %	Manganese. %	Sulphur. %	Phosphorus. %	Nickel. %	Chromium. %	Special Elements. %
Crucible steel 1	0.22	...	0.08	...	...	...	...
" 2	0.48	...	0.18	...	...	...	...
" 3	0.71	...	0.18	...	...	...	...
" 4	0.90	...	0.18	...	...	...	...
" JW	0.13	0.02	0.46	0.025	0.006	Trace	0.01	
ZSFC	0.14	0.04	0.76	0.108	0.112	...	...
ZCH	0.15	0.05	0.56	0.031	0.033	...	...
N	0.38	0.24	0.64	0.016	0.022	...	0.10	
L	0.51	0.13	0.68	0.015	0.029	0.12	...	
AL	0.52	0.35	0.48	0.020	0.011	0.15	...	
AH	0.57	0.27	0.59	0.012	0.017	0.16	...	
DL	0.10	0.10	0.25	0.022	0.008	0.17	0.05	
DH	0.15	0.13	0.29	0.010	0.015	5.02	...	
CL	0.26	0.09	0.37	0.032	0.026	5.11	0.15	
J	0.27	0.21	0.55	0.009	0.012	3.52	0.53	Vanadium, 0.18
K	0.32	0.26	0.44	0.010	0.013	2.93	1.38	
CH	0.40	0.44	0.48	0.032	0.025	4.22	1.35	
BL	0.21	0.11	0.48	0.018	0.014	3.60	0.68	
BH	0.27	0.20	0.42	0.015	0.023	2.95	1.23	Molybdenum, 0.16
SD	0.40	0.07	1.16	0.020	0.011	2.98	1.31	Molybdenum, 0.44
U	0.66	0.23	0.31	0.005	0.021	Trace	0.01	
Q	1.22	0.14	0.31	0.012	0.018	0.13	0.10	Tungsten, 6.18
						0.07	...	

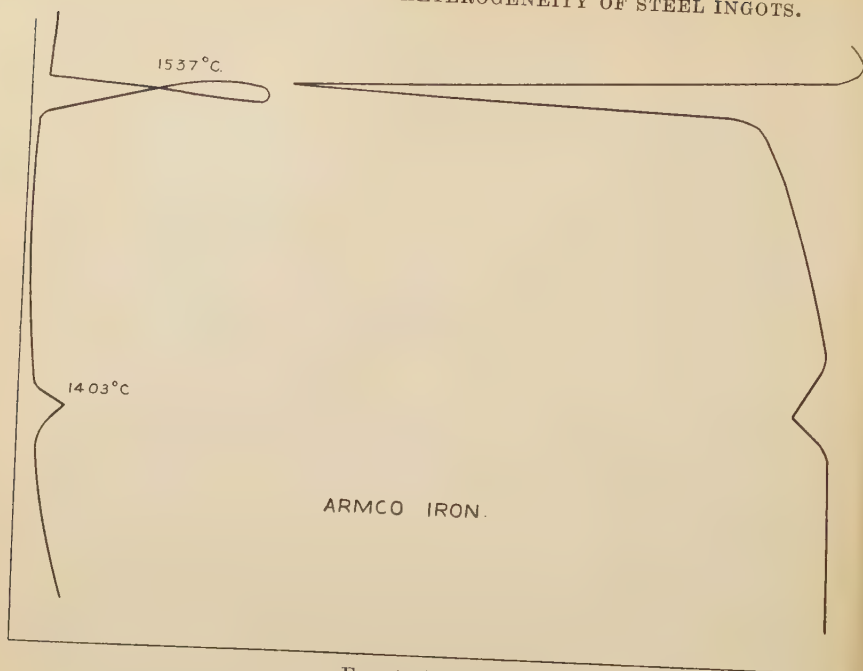


FIG. 4, A.

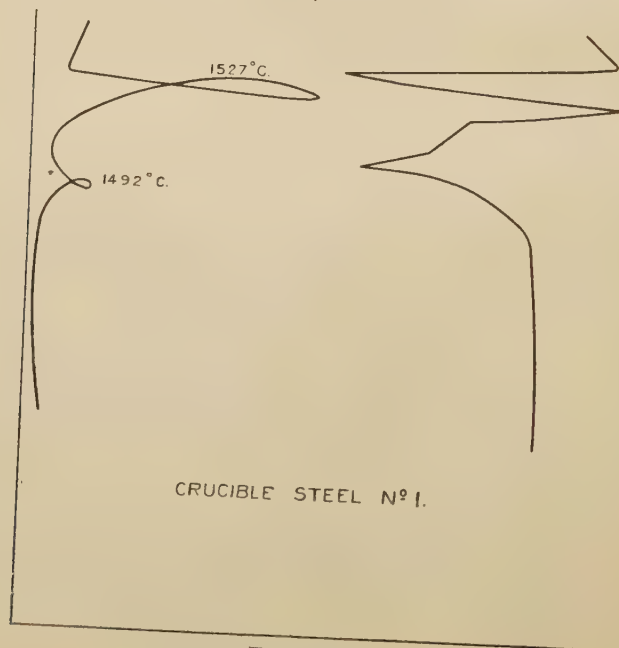


FIG. 4, B.

(For analyses, see Table I., p. 319.)

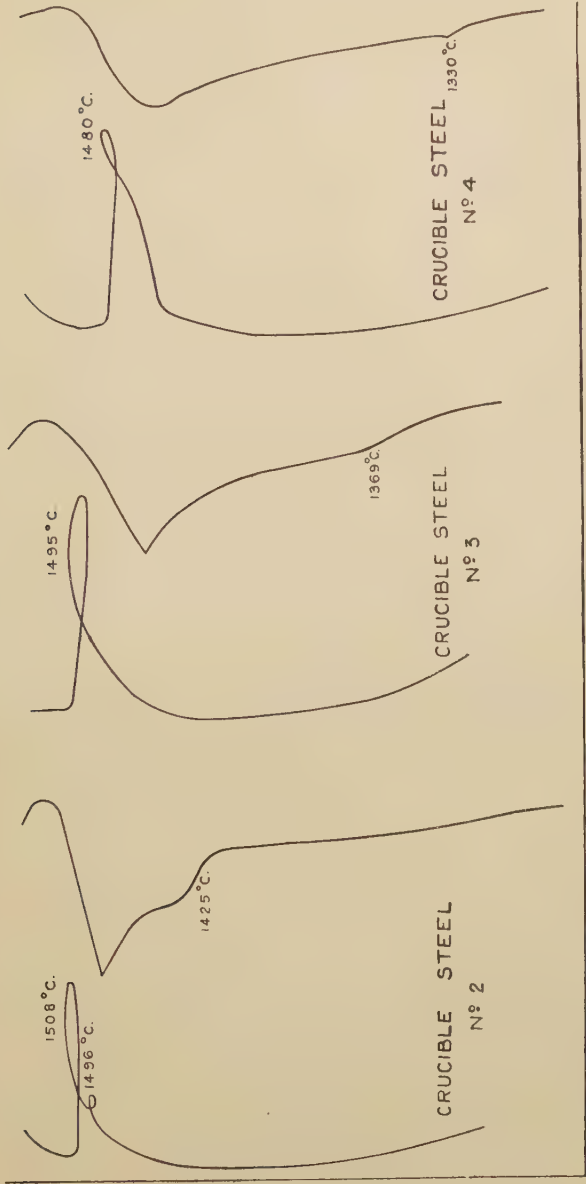


FIG. 4, E.

FIG. 4, D.
(For analyses, see Table I., p. 319.)

FIG. 4, C.

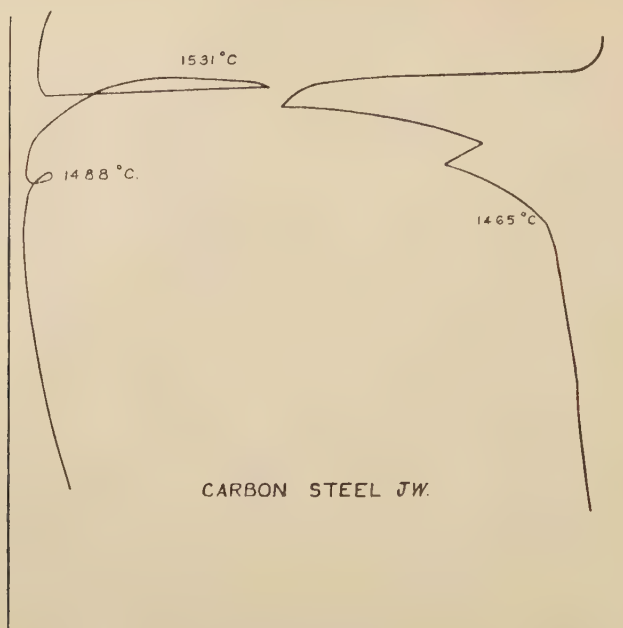


FIG. 4, F.

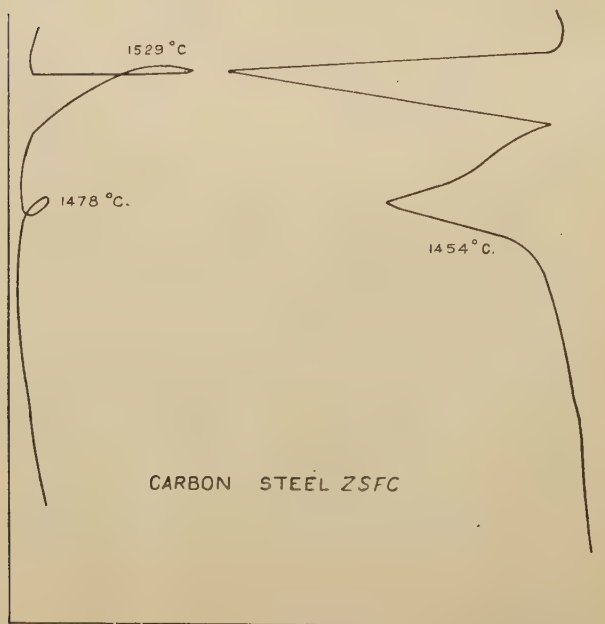


FIG. 4, G.

(For analyses, see Table I., p. 319.)

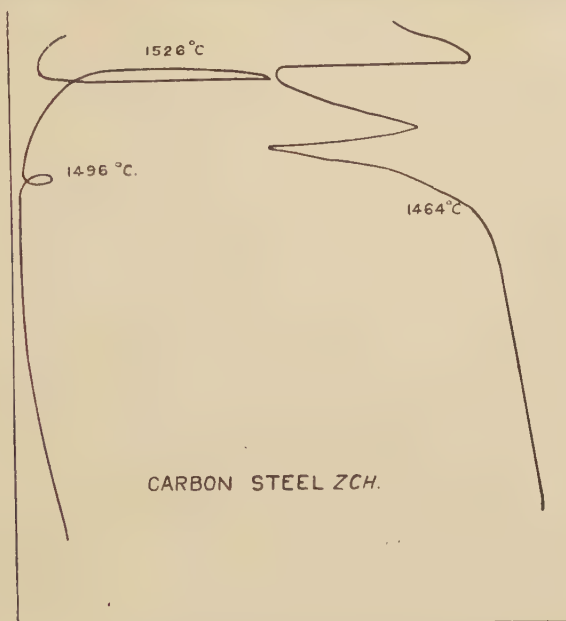


FIG. 4, H.

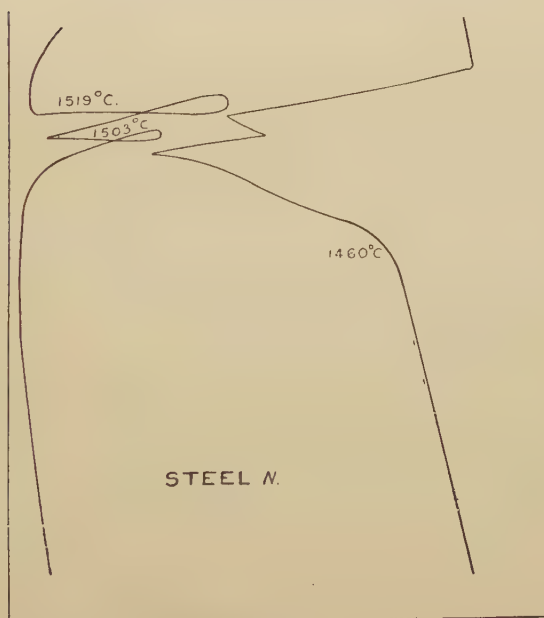


FIG. 4, J.

(For analyses, see Table I., p. 319.)

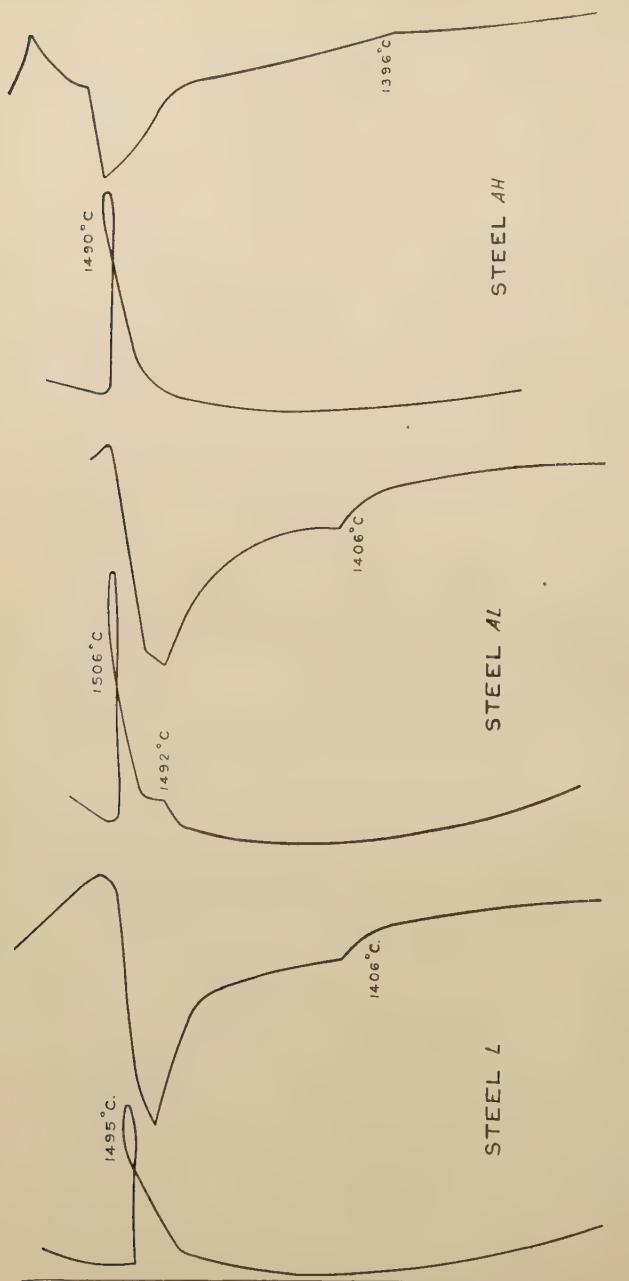


Fig. 4, K.

Fig. 4, L.

(For analyses, see Table I., p. 319.)

Fig. 4, M.

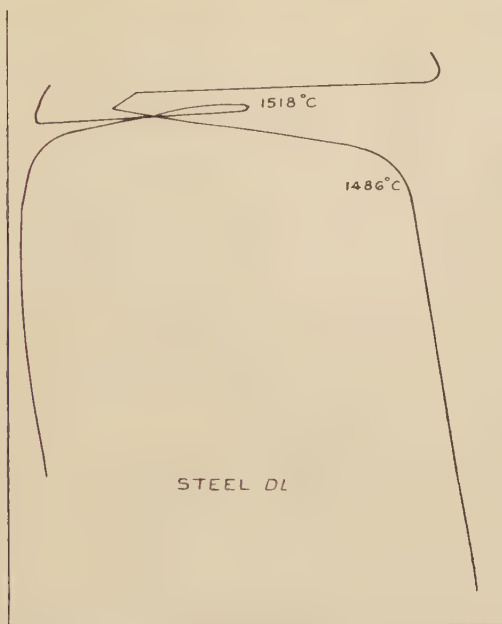


FIG. 4, N.

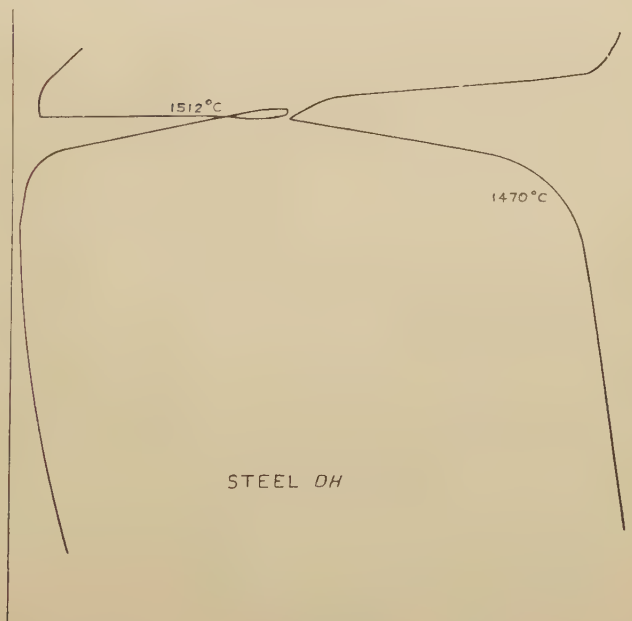


FIG. 4, O.

(For analyses, see Table I., p. 319.)

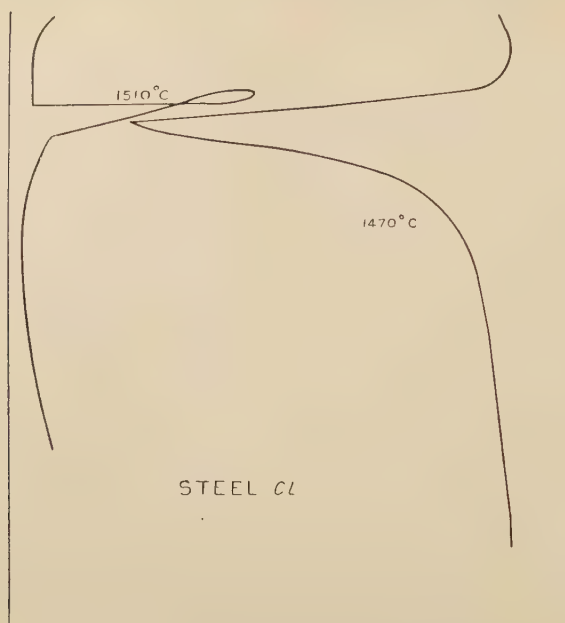


FIG. 4, P.

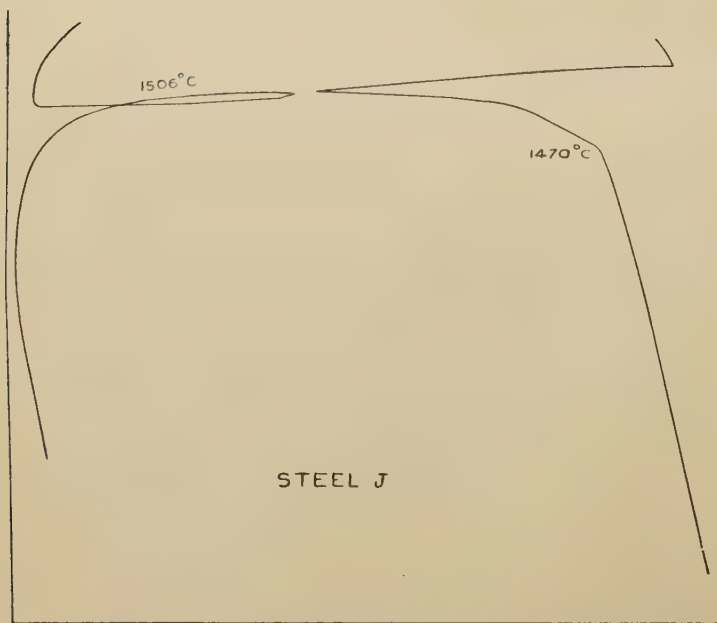


FIG. 4, Q.

(For analyses, see Table I., p. 319.)

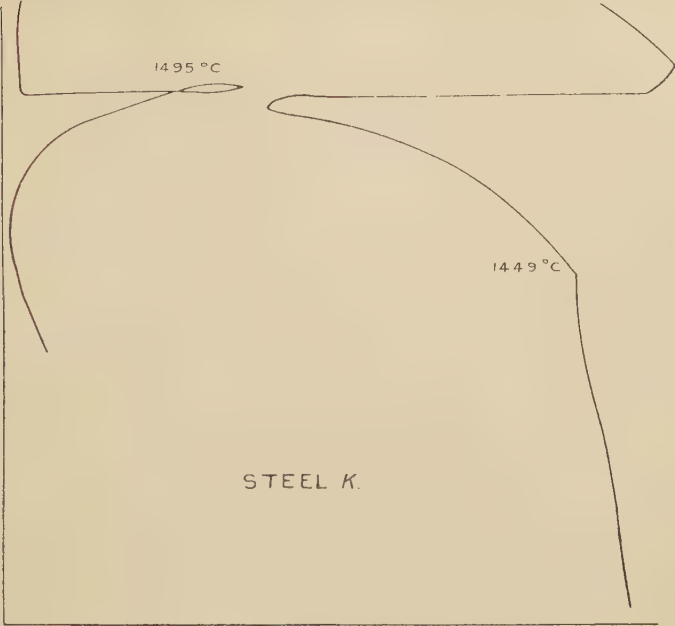


FIG. 4, R.

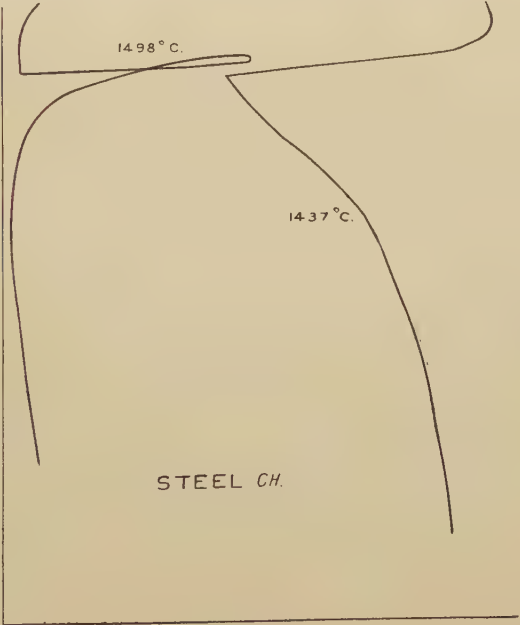


FIG. 4, S.

(For analyses, see Table I., p. 319.)

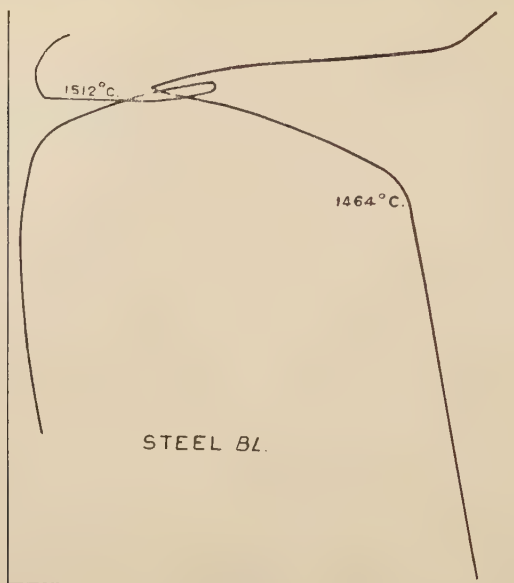


FIG. 4, T.

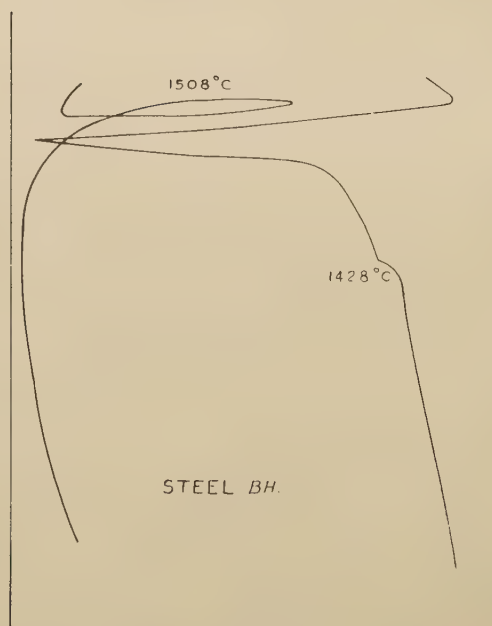


FIG. 4, U.

(For analyses, see Table I., p. 319.)

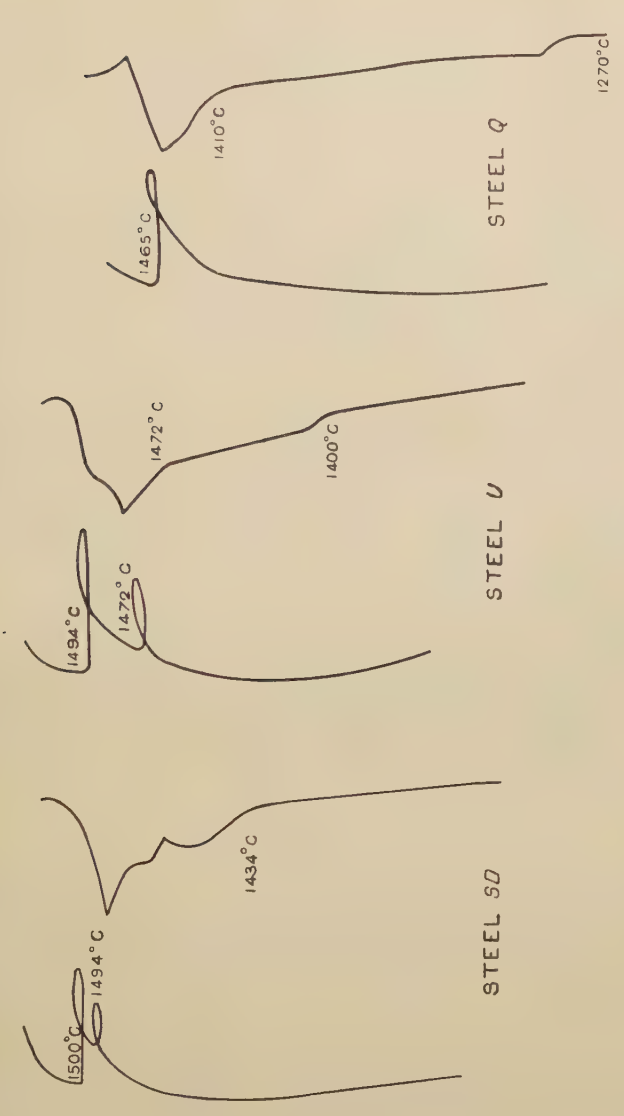


FIG. 4, V.

FIG. 4, W.

FIG. 4, X.

(For analyses, see Table I., p. 319.)

The Armco iron was melted without the protection of a carborundum covering, so that its complete decarburisation was assured. The value for the freezing and melting point obtained by the tungsten-molybdenum couple was 1537°C. , a figure advocated by Carpenter. The δ - γ transformation occurred at 1403°C. , which agreed with the results of the Japanese workers.

The freezing and melting points of the other steels require but little comment. It should be mentioned that the peritectic transformation was detectable in steels Nos. 1 and 2 only. The mean value for this transformation was 1494°C. , which is the melting point of the 0.71 per cent. carbon steels. The peritectic would, therefore, according to these figures, extend to 0.71 per cent. of carbon.

In Fig. 5 a straight line has been drawn for the liquidus and another for the solidus. These lines are approximations only, and it is not for a moment considered that these few determinations, made on steels which are not of 100 per cent. purity, are suitable data with which to establish a complete and absolutely accurate iron-carbon equilibrium diagram.

The curves for the commercial steels are given in Fig. 4, *F* to *X*. For convenience in dealing with these steels they will be divided into two categories—namely, carbon steels and nickel and nickel-chromium steels, the latter class including two molybdenum steels and one vanadium steel.

Carbon Steels.

Steel JW.—The only impurity of any moment is manganese. The freezing point falls on the theoretical curve, and the peritectic transformation occurs at 1488°C. , just 6°C. lower than the normal. The γ -($\delta + \gamma$) transformation agrees well with the theoretical value.

Steel ZSFC.—This steel is of the same carbon content as steel *JW*, but has a high phosphorus content. This impurity is no doubt responsible for the slight lowering of the freezing point, and the greater lowering of the peritectic transformation. The point at 1454°C. on heating is consistent with the lowering

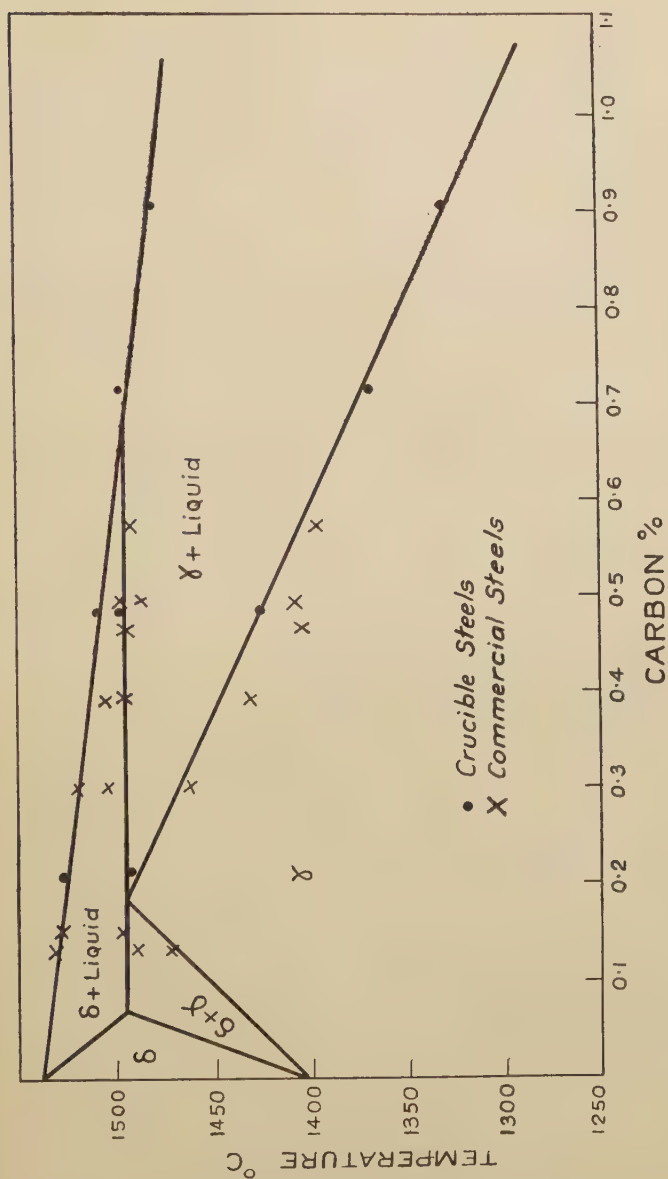


FIG. 5.

of the peritectic change, this change being undoubtedly the γ -($\delta + \gamma$) transformation.

This result fits in with the work of Haughton, who has shown the remarkable lowering of the δ - γ change, which at 0.6 per cent. of phosphorus brings about the complete elimination of the γ phase.

Steel ZCH.—The only impurity of importance is manganese. All points fit in well with the diagram.

Steel N. The freezing and melting points agree well with the diagram. A peculiar feature of this sample is that the peritectic change on freezing occurs at a higher temperature than it does on melting.

Steel L.—Both the freezing and melting points of this steel were low. There is the possibility that the high manganese content might be responsible for this; there is some evidence that manganese above 0.6 per cent. has an effect on the mechanical and other properties of steel which does not occur when the manganese content is below about 0.55 per cent.

Steel AL.—All points fit in well with the diagram; this was unexpected in view of the high silicon content. The presence of a small peritectic point should be noted. It was absent in steel *L* of lower carbon content, on account most probably of the higher manganese content.

Steel AH.—The freezing point is low, due to the high manganese content.

Summary of Carbon Steels.—With one exception (steel *ZSFC* is not regarded as a plain carbon steel on account of the high phosphorus), namely, steel *L*, all the samples gave points which fitted in with the theoretical diagram remarkably well. Manganese up to about 0.55, and silicon up to about 0.35 per cent., are, so far as the specimens examined have shown, quite without effect on either the freezing or melting points. This is extremely fortunate, for it enables the iron-carbon diagram to be used for commercial steels without objection.

Nickel and Nickel-Chromium Steels.

Since these steels contain varying amounts of nickel and chromium, it is difficult to plot the results on any one diagram.

For the sake of comparison, however, the results are plotted on the theoretical iron-carbon diagram. By doing so, many points of interest are brought to light. The curves for the nickel and nickel-chromium steels will therefore be dealt with generally, and with respect to their position of the freezing and melting points shown in Fig. 6. The two nickel-chromium-molybdenum steels are also included.

If the nickel and chromium contents of each steel be added together, and the difference between its freezing point and that of a carbon steel of the same carbon content be estimated, the calculation of the ratio of the latter value to the former produces an interesting set of figures, as follows :

Steel.	Ni + Cr Contents. %	Temperature Difference. ° C.	Ratio.
<i>BL</i>	4.16	19	4.5
<i>BH</i>	4.2	20	4.7
<i>CL</i>	4.0	19	4.7
<i>CH</i>	4.2	25	6.0
<i>DL</i>	5.1	17	3.4
<i>DH</i>	5.2	22	4.4
<i>J</i>	4.4	22	5.0
<i>K</i>	5.7	28	5.0

With two exceptions—namely, steels *DL* and *CH*—the depression of the freezing point due to nickel and chromium varies between 4.4° and 5° C. for every 1 per cent. of combined nickel and chromium present (by combined nickel and chromium is meant the sum of the amounts of these two elements in the steel). It will be noticed that the two molybdenum steels fall into line with this calculation. With regard to these last-mentioned steels, a most noticeable feature is the solidus temperature, which in both cases lies well below the solidus line of the iron-carbon diagram, the difference between the freezing and melting point being greater the larger the percentage of molybdenum present in the alloys. This supports the contention of Westgren, who has experimentally shown that molybdenum separates in the form of a molybdenum-iron carbide. The fact that the solidus line obtained with the nickel and nickel-chromium steels almost coincided with that for carbon steels suggests that these elements do not separate as carbides, but that they exist rather in solid solution in the iron-carbon system.'

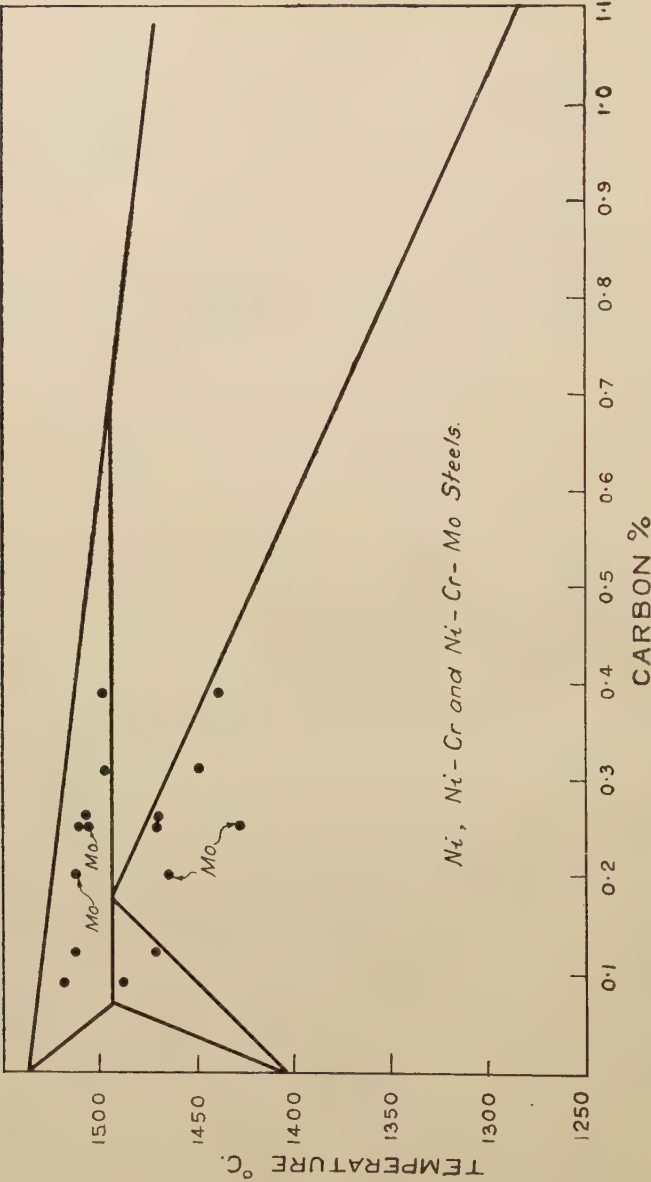


FIG. 6.

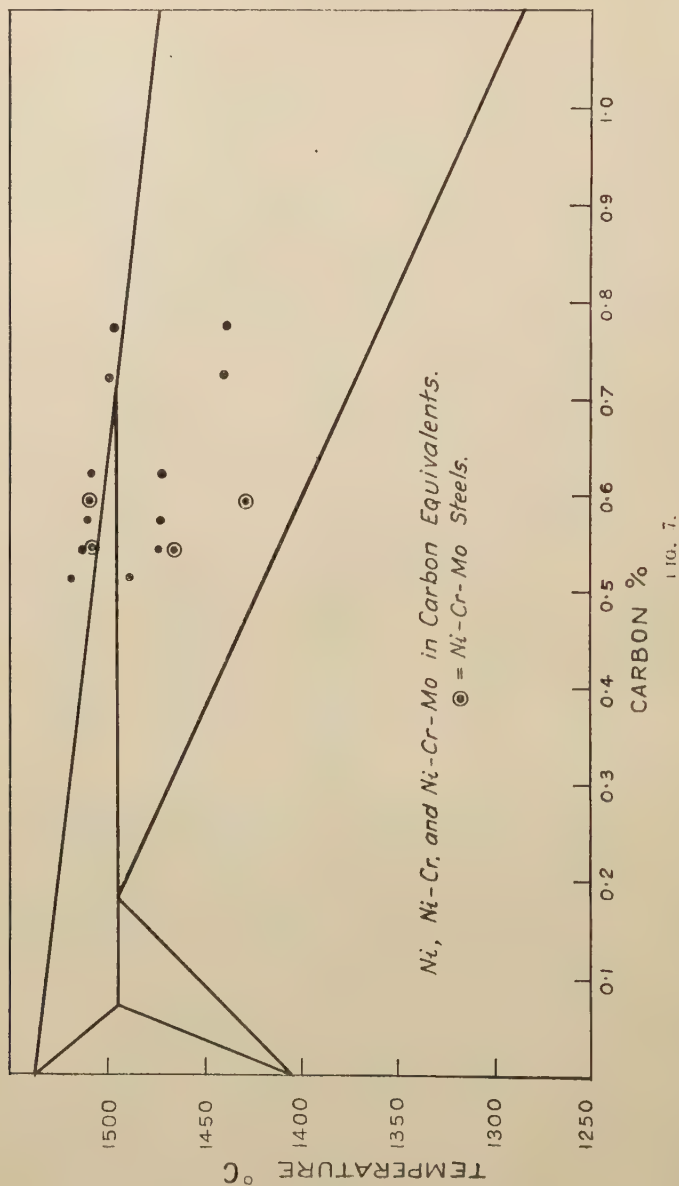
If, then, the nickel and chromium contents of any steel of low nickel and chromium content be added together, and the figure so obtained be multiplied by 4·8, the result will give the approximate lowering of the freezing point due to nickel and chromium, so that by utilising the iron-carbon diagram a fairly accurate figure for the actual freezing temperature of the alloy may be obtained. Further, since the solidus line of the alloy steels has been found to correspond closely with that of the carbon steels, the melting points may be deduced.

Another way of plotting the results obtained with the alloy steels is as follows: According to Hanson, 4 per cent. of nickel lowers the freezing point by the same amount as 0·33 per cent. of carbon. Assuming that chromium has a similar effect, if the total nickel plus chromium content be multiplied by the factor $0\cdot33$
 $\frac{4}{4} = 0\cdot082$, the carbon equivalent for the nickel plus chromium will be obtained, thus:

Steel.	Nickel + Chromium. %	Ni + Cr \times 0·082.	Carbon. %	Total Carbon Equivalent.
<i>BL</i>	4·16	0·34	0·20	0·54
<i>BH</i>	4·2	0·34	0·25	0·59
<i>CL</i>	4·0	0·32	0·25	0·57
<i>CH</i>	4·2	0·34	0·38	0·72
<i>DL</i>	5·1	0·42	0·09	0·51
<i>DH</i>	5·2	0·42	0·12	0·54
<i>J</i>	4·4	0·36	0·26	0·62
<i>K</i>	5·7	0·46	0·31	0·77

It is seen from Fig. 7, in which these results are plotted, that the liquidus lies very close to the liquidus of the pure iron-carbon steels, whilst the solidus lies much closer to the liquidus than it does in the theoretical iron-carbon diagram. This serves as another means of calculating the freezing temperature of nickel and chromium steels.

Hanson's figure of 0·082 has been taken in preference to that calculated from the commercial steels, because it gives a relation between pure nickel-iron alloys and carbon, without the intervening action of impurities. The assumption that chromium behaves similarly to nickel when in small quantities does not seem to have introduced any appreciable error. It will be noticed that the freezing points in Fig. 7 lie about 5° C. above the theoretical liquidus.



*The Relation between the Liquidus and Solidus Limits,
and the Homogeneity of Steels.*

Two reasons for the greater homogeneity of nickel and nickel-chromium steels, as compared with carbon steels, arise out of this investigation. In the first place, the liquidus and solidus curves for the alloy steels—*i.e.* nickel and nickel-chromium—lie nearer together with respect to temperature than they do in the case of plain carbon steels. This necessarily means that solidification takes place over a narrower range of temperature, and therefore relatively more rapidly. It further implies a smaller difference in carbon content at any corresponding temperature between the liquid and solid during freezing. Secondly, in the nickel and nickel-chromium steels dealt with, whilst it cannot be definitely said that the peritectic transformation was absent, it did not appear in any of their curves.

A peritectic transformation is regarded as a constant temperature reaction between a liquid *C* and a solid *A*, with the formation of a new solid *B* (see Fig. 9). Any alloy to the right of *B* (with respect to the composition axis) should, therefore, just at the peritectic temperature and under conditions of equilibrium, consist entirely of *B* along with liquid *C*. It is difficult to conceive that that reaction takes place to completion during the solidification of an ingot.

A more rational way of viewing this type of change is to regard it as a sudden change from one solidus system to another.¹ Since in the iron-carbon system the new solidus system (on cooling) is associated with a higher carbon content, it is obvious that at the peritectic temperature an excess amount of liquid (as compared with that solidifying at any one temperature above the peritectic line) will freeze. It is, then, the freezing of this excess liquid, along with a change from δ - to γ -iron, that gives rise to an evolution of heat at this temperature.

In carbon steels, between the temperature of freezing and that of the peritectic, iron containing a maximum of 0.07 per cent. of carbon is the only solid to separate. For the steel to become homogeneous with respect to carbon, a diffusion of this

¹ A special note has been added on peritectic changes at the end of this section.
1929—i.

element must necessarily occur in the solid, and provided the steel remains at a temperature above 1350°C . for a sufficiently long time homogeneity with respect to carbon may be brought about. There is, however, much evidence pointing to the fact that complete diffusion may not always occur. It is only necessary to bring to mind the extreme slowness with which the cemented layer of a case-hardened steel diffuses inwards, even at a comparatively high temperature, to realise that diffusion of carbon is not a rapid reaction.

If, as appears to be the case, nickel and nickel-chromium steels of the composition dealt with undergo no peritectic change, then it can be assumed that a solid containing relatively large amounts of carbon will form as solidification proceeds.¹ The diffusion necessary to bring about homogeneity will then have to take place to a less degree than with carbon steels, as two solid phases are not originally present. The two molybdenum steels examined are of interest, inasmuch as in these steels the temperature distance between the liquidus and the solidus is the greatest of all samples investigated. The molybdenum steel referred to in the Second Report² shows a marked segregation of molybdenum and carbon, a high carbon content being associated, generally speaking, with a high molybdenum content. This is confirmatory evidence of the effect of the liquidus-solidus range upon segregation, and the results suggest that molybdenum segregates in the form of molybdenum carbide. Reverting to carbon steels, a peculiar feature of the heating curves was that, provided the solidus was above 1400°C ., the first heating curve usually showed a number of breaks at temperatures about 1400°C . In a repeat determination, provided the sample was not cooled below 900°C . before reheating, these breaks were absent. It was quite an easy matter to distinguish the solidus point from these irregular deviations, which were always in the nature of an absorption of heat. It should be added that in every case the solidus point in the second curve coincided exactly with that in the first.

An explanation which fits in well with the facts is as follows: The heating of an experimental specimen, although comparatively

¹ That is, the composition is such that the liquid passes directly to the γ phase.

² *Journal of the Iron and Steel Institute*, 1928, No. I. p. 401 (see p. 423).

slow, is rapid as compared with the heating of an ingot or billet. This being the case, on heating, the carbon had not sufficient time to diffuse completely through the original free α -iron, which at 900° C. becomes changed into γ -iron. The result would then be that this comparatively pure iron would undergo the γ - δ transformation at a temperature dependent upon its carbon content. The almost pure iron would transform around 1403° C. to δ -iron, and that containing small amounts of carbon at temperatures corresponding to its carbon content. Upon melting and cooling down to 900° C., the specimen would be at a high temperature for sufficient time for a certain amount of diffusion

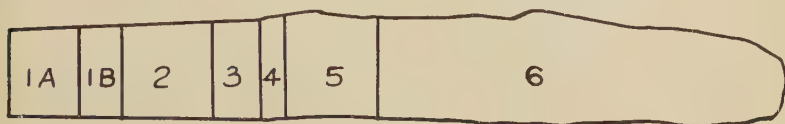


FIG. 8.

to take place, enough probably to mask any small high temperature change that might occur.

An experiment which shows the effect of diffusion of carbon upon the structure of steels was made as follows: A bar of a steel containing carbon 0.46, manganese 0.2, and silicon 0.2 per cent. was sectioned so as to give a specimen 10 cm. long and about 2 cm. round. This was completely encased in alundum, and an outer coating of carborundum. It was placed in the furnace so that one end became completely melted and the other end remained well below the melting point. It was allowed to remain in the furnace at its highest temperature for 1 hr., after which it was slowly cooled with a current passing through the furnace. It was then sectioned vertically through the centre, and a micro-examination was made of the inside surface.

Six micrographs were sufficient to depict the variation of structure along the bar; these are shown in Figs. 10 to 15 (Plates XXXVI. to XXXVIII.), and the areas to which the micrographs correspond are indicated in Fig. 8.

Fig. 10 shows the line of demarcation between areas 1A and 1B. Area 1A represents what might be taken as a typical normalised structure. In the area 1B the structure was that of

a drastically overheated steel. It will be evident that diffusion of carbon had occurred to a marked extent, and that the whole configuration of the ferrite had changed. This line of demarcation between the temperature of overheating and of normalising appeared as a clear line right across the specimen. Fig. 11 is typical of the structure within area 2, which consisted almost entirely of large sorbitic grains with but little free ferrite. This was brought about either by a most uniform diffusion of the carbon, or by a Soret effect, causing migration of the carbon from the hot to the cooler region. Fig. 12 shows that incipient melting had obviously occurred in area 3; the material composing the interior of the grains had become fluid, whilst the grain boundaries of iron (ferrite) had remained solid.

Fig. 13 demonstrates that in area 4 the temperature was obviously just above the peritectic transformation; the carbon-rich solution had separated from the iron, leaving the latter, along in all probability with a certain amount of γ -iron containing a maximum carbon content of 0.18 per cent., which had given rise to the pearlite on cooling.

In area 5 (Fig. 14) melting had been nearly complete, but the carbon content was less than that of the normal steel, while in area 6 (Fig. 15) the melting had been complete, the coarse structure being that of a carbon steel which had been kept molten for some time.

These micrographs lead to the following considerations :

(1) Diffusion of carbon is not sufficiently rapid to bring about homogeneity with respect to this element. Although the specimen dealt with in the above experiment was relatively insignificant as compared with a large ingot, it was established that in the present instance diffusion did not take place to any marked degree. The view that even in large carbon steel ingots diffusion of carbon occurs to a far less extent than is usually assumed receives some support. It would almost seem that diffusion does not occur on a falling temperature.

(2) The structure of area 6 was far coarser than that of specimens melted in the usual manner (prior to taking a freezing curve). This suggests that time and the temperature of the melt have an effect on the grain-size, the higher the temperature and the longer the time in the molten state, the larger being the

grain-size of the resulting material. Since the furnace was run for an hour with the same current as was required for melting the specimens for freezing-point determinations, it is obvious that the temperature must have been higher.

(3) The line of demarcation between overheating and not overheating is exceedingly sharp.

The Interpretation of the Peritectic Transformation.

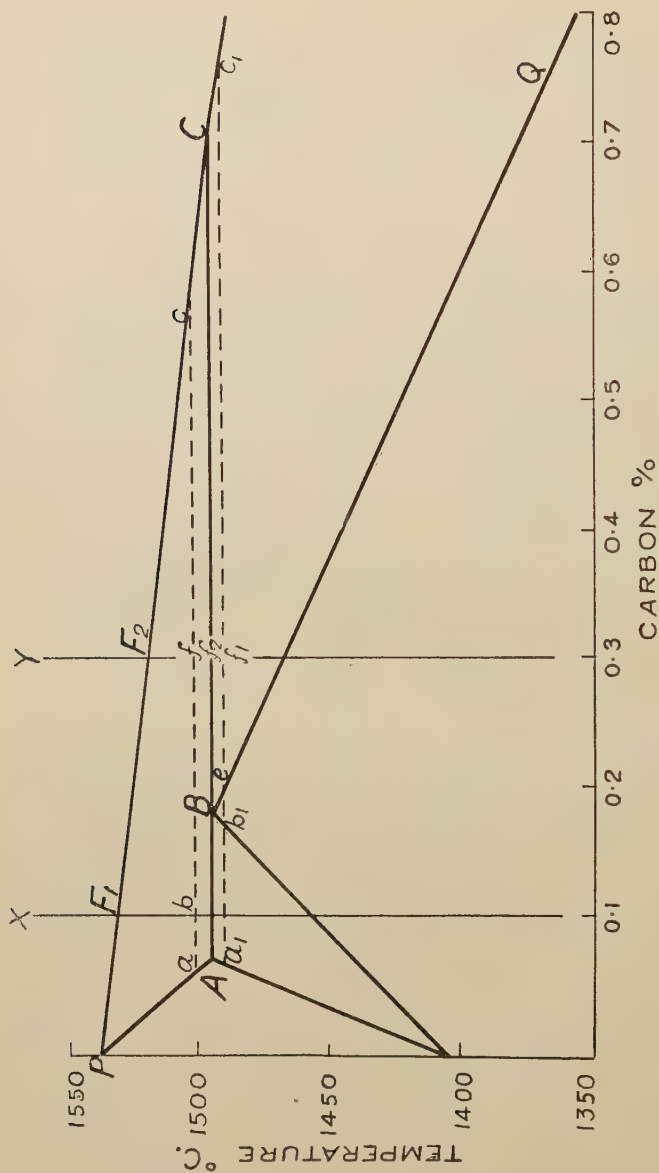
In view of the experimental evidence contained in this Report, the peritectic transformation assumes an importance not usually attached to it. The method of interpreting the mechanism of a transformation of this type as given by many authorities is, however, misleading, and it was thought that a note dealing with the matter might be of value. Fig. 9 has been drawn to illustrate the discussion.

The explanation usually given is as follows : At the temperature of the peritectic, a reaction occurs between a liquid phase and a solid phase, which gives rise to the formation of a new solid phase. In Fig. 9, for instance, the reaction may be expressed by :



This, it is assumed, is responsible for the evolution of heat at the constant temperature of the peritectic. Further, it is generally imagined that, in an alloy of composition denoted by Y in the figure, at the peritectic temperature the whole of the solid A will react with the liquid C and be completely changed to the solid B , with some liquid remaining. A change of this character is not, however, in accordance with the phase law, which demands the existence of three phases at the peritectic temperature.

A simpler method of regarding this type of transformation is to consider it as belonging to two separate systems, a transference from one to the other occurring at the peritectic temperature. In this case the transference is from a δ -iron system containing but a small quantity of carbon in solution, to γ -iron containing a greater amount of carbon in solution. An alloy of composition X will begin to freeze in the δ form at a



temperature denoted by F_1 ; at a temperature b there will be present bc of solid (δ -iron with some carbon in solution) and ab of liquid (which will contain the greater part of the carbon).

At the peritectic temperature three phases must be present, namely, solid A , solid B , and liquid C , whilst just below the peritectic temperature only two phases, namely, a_1 and b_1 , can co-exist in equilibrium. It is thus seen that the formation of the b_1 phase (γ -iron with carbon in solution) takes place largely in the solid. This being so, immediately after solidification the steel will be far from homogeneous, and will consist of areas of iron almost free from carbon, originally deposited in the δ form, and areas higher in carbon. In practice it is most probable that the alloy of this composition will not become completely solid at a temperature b_1 , but that the liquid will continue to freeze along BQ until the last portions have become solid.

As a second example, consider an alloy of composition Y . Freezing will begin at F_2 , and at a lower temperature, f , there will be present relatively af of liquid and fc of solid (δ -iron with some carbon in solution). Below the peritectic temperature, at f_1 , when equilibrium has been established there would be relatively f_1c_1 of the B constituent, and ef_1 of the liquid remaining. It is thus seen that as the peritectic change is passed through the solidus changes from PA to BQ , and an amount of solid approximately equal to $(Af_2 - Bf_2)$ will separate and freeze spontaneously. This amount is equal to AB in the diagram, and it is this deposition, along with the change from δ - to γ -iron, which is responsible for the heat evolution at the peritectic.

Experimental freezing curves have always shown up the peritectic as a marked and sudden change, occurring over a very short period of time. The sharpness of the point leaves no doubt as to its not being due to the interaction of two phases. Further, it will be evident that in any change which involves a transference from one system to another there will always be a tendency for the liquid phase to be more concentrated in the solute element (carbon in this case), so that equilibrium can only be established by prolonged heating of the alloy in the solid state.

Microstructures of Specimens used for Freezing-Point Determinations.

Typical structures of the varying types of steel used in the melting and freezing point determinations are shown in the six micrographs, Figs. 16 to 21 (Plate XXXIX.). They were taken after the freezing-point determination, without the specimen having been submitted to any subsequent treatment.

Steel AL (Fig. 16).—This is a plain carbon steel containing 0.52 per cent. of carbon and 0.48 per cent. of manganese. The light area low in carbon represents what was in all probability a large δ -iron area in the high-temperature state. The absence of any large amount of carbon in this area accounts for the relatively high carbon content of the remainder. This micrograph is typical of the whole specimen.

Steel SD (Fig. 17).—Although this steel contained 0.40 per cent. of carbon and 1.16 per cent. of manganese, and showed a small peritectic transformation, the fact that this transformation occurred within 6° C. of the freezing point would tend to make it ineffective in markedly affecting the structure. The increased homogeneity and absence of large ferrite areas due to a high manganese content is evident.

Steel ZSFC (Fig. 18).—This steel contained 0.14 per cent. of carbon and 0.11 per cent. of phosphorus. The structure illustrates well the effect of elements, such as phosphorus, which tend to lower the δ - γ change. By increasing the stability of δ -iron at a low temperature, the carbon that has concentrated in the small areas of γ -iron appears finally as small isolated areas of pearlite, which in many places is almost in the form of free cementite. This should be compared with specimen *SD*, where the contrary effect of manganese, by decreasing the amount of δ -iron and increasing that of the γ form, has brought about a better diffusion of the carbon.

Steel DH (Fig. 19).—This is a high-nickel low-carbon steel containing 5.11 per cent. of nickel and 0.15 per cent. of carbon. The freezing point showed no peritectic transformation, the iron therefore solidifying completely in the γ form, with the result that the carbon is exceedingly well diffused.

Steel K (Fig. 20).—This is a nickel-chromium steel containing



FIG. 11.—Area 2 of Fig. 8.



FIG. 10.—The line of demarcation between areas 1A and 1B in Fig. 8.

Micrographs of a steel containing Carbon 0.46, Manganese 0.2, and Silicon 0.2 per cent. $\times 125$; reduced in reproduction to $\frac{2}{3}$.

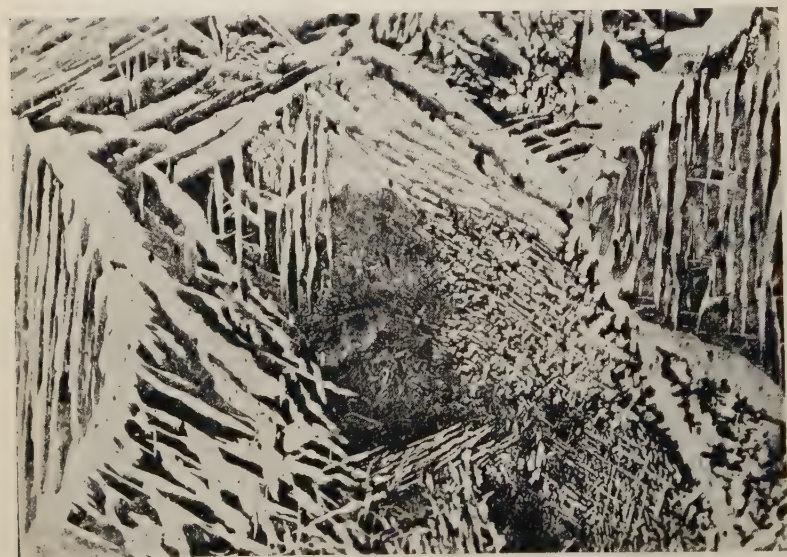


FIG. 12.—Area 3 of Fig. 8.

Micrographs of a steel containing Carbon 0.46, Manganese 0.2, and Silicon 0.2 per cent. $\times 125$, reduced in reproduction to $\frac{1}{3}$.



FIG. 13.—Area 4 of Fig. 8.

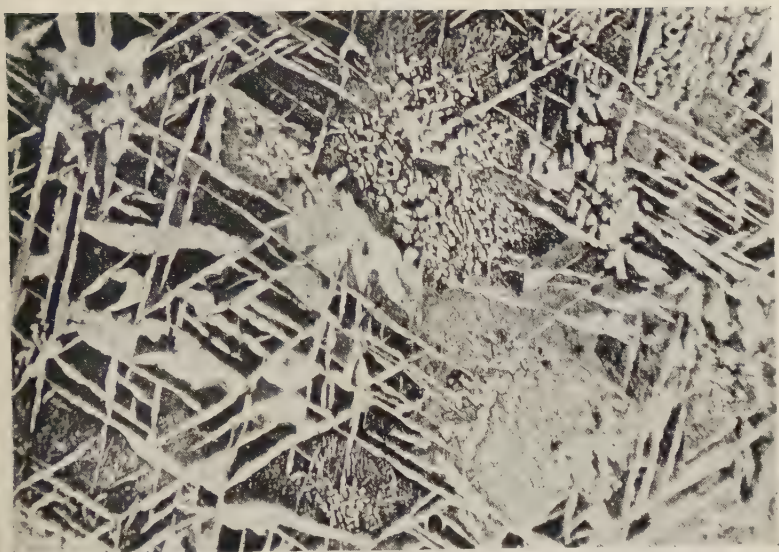


FIG. 15.—Area 6 of Fig. 8.

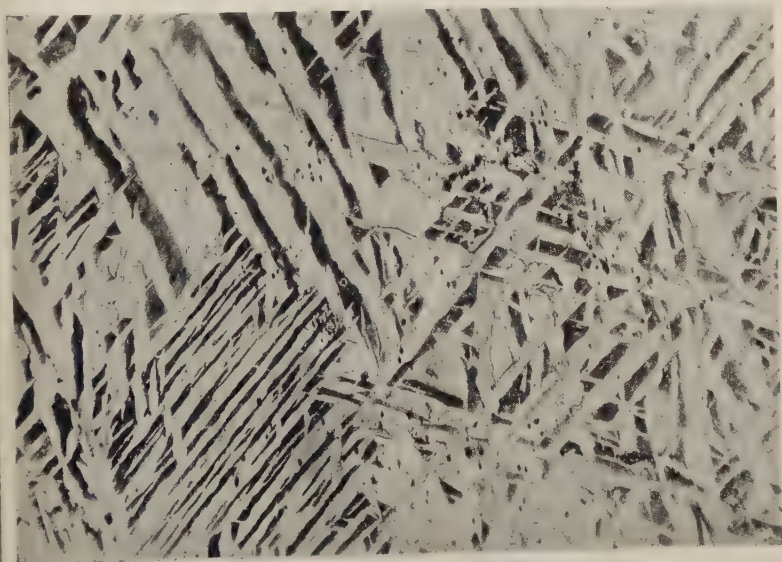


FIG. 14.—Area 5 of Fig. 8.

Micrographs of a steel containing Carbon 0.46, Manganese 0.2, and Silicon 0.2 per cent. $\times 125$; reduced in reproduction to $\frac{3}{4}$.

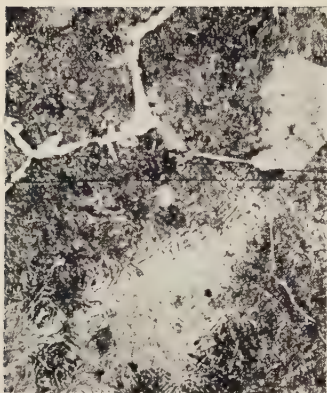


FIG. 16.—Steel AL.



FIG. 17.—Steel SD.



FIG. 18.—Steel ZSFC.



FIG. 19.—Steel DH.



FIG. 20.—Steel K.



FIG. 21.—Steel BH.

Magnification $\times 60$; reduced in reproduction to $\frac{2}{3}$.

0·32 per cent. of carbon, 4·22 per cent. of nickel, and 1·35 per cent. of chromium. Except for the white areas, which may possibly be areas high in one of the alloying elements, the steel, as is to be expected, is homogeneous, and the carbon fairly uniformly distributed.

Steel BH (Fig. 21).—This is a nickel-chromium-molybdenum steel containing 0·27 per cent. of carbon, 2·98 per cent. of nickel, 1·31 per cent. of chromium, and 0·44 per cent. of molybdenum. The segregation of molybdenum carbide referred to previously is borne out by the micrograph; in some cases the white areas would appear to be free carbide, but more usually they are austenite.

Conclusions.

1. It has been shown that the liquidus and solidus curves of the commercial steels dealt with conform with respect to carbon content and temperature with the iron-carbon diagram, provided the manganese is below 0·45 per cent.

2. Nickel-chromium and nickel steels freeze at a lower temperature than plain carbon steels, the temperature depending upon the nickel and chromium contents. The melting points or solidus occur at approximately the same temperature as they do in plain carbon steels of the same carbon contents. A method has been given for calculating the freezing and melting ranges of low-nickel and low-chromium steels.

3. Nickel-chromium steels containing molybdenum differ from nickel-chromium steels without molybdenum in that, whilst their freezing points are not affected by the small quantities of molybdenum present, their melting points or solidus appear to be considerably lowered by the molybdenum in proportion to the amount present.

4. The explanation has been advanced that nickel and nickel-chromium steels tend to show less segregation with respect to the carbon, for two reasons. First, the liquidus and solidus lines lie nearer to one another with respect to temperature than they do in a plain carbon steel, and, secondly, in steels in which the peritectic transformation has been obliterated, this in itself will account for their greater homogeneity.

5. Nickel-chromium steels containing molybdenum will show

a segregation of molybdenum carbide, on account of the widening of the liquidus-solidus range by that compound. It is a necessary inference that metals which form a solid solution with the iron phase depress the freezing point only, whilst metals which form a carbide depress the solidus limit with respect to temperature.

6. Micrographs have been shown of various sections from a specimen differentially heated and melted at one end; they emphasise the importance of the peritectic reaction in carbon steels, and also indicate that the diffusion of carbon is much less rapid than is usually assumed. Whilst the time during which a large ingot will remain at a temperature at which diffusion may be fairly rapid is longer than it is for a smaller ingot, on the other hand the longer time taken to cool through the peritectic may balance or overbalance this effect; it may bring about a more complete separation of the two phases, δ -iron and solid solution.

7. The liquidus and solidus curves derived from carbon steels run almost parallel with those of Carpenter and Keeling.

The authors would like to express their indebtedness to the Council of the Iron and Steel Institute for having contributed towards the cost of this and the following investigation, and for having awarded a grant of £100 from the Carnegie Research Fund to Dr. Binnie. Further, they wish to thank Dr. Hatfield and other members of the Committee on Heterogeneity of Steel Ingots, not only for having provided the necessary steel samples together with their analyses, but also for their sympathetic interest in these rather difficult pieces of research.

SECTION III.—THE SOLUBILITY OF IRON AND MANGANESE SULPHIDES IN STEEL.

By Professor J. H. ANDREW, D.Sc., and DAVID BINNIE, B.Sc.,
Ph.D., A.R.T.C. (Carnegie Scholar) (Glasgow).

It is usually assumed that, provided the manganese content of a steel is sufficient, all the sulphur present is out of solution, and exists in the form of MnS, or a complex of MnS with oxides of iron and manganese, and possibly FeS.

The particular form in which sulphur exists in the molten steel is not known, but it is the opinion of many steel smelters that FeS prevails, even in the presence of manganese, at the high temperature of the Siemens furnace, the formation of MnS taking place just prior to or simultaneously with the solidification of the steel.

That the reaction $\text{FeS} + \text{Mn} = \text{MnS} + \text{Fe}$ is reversible is most probable, and from the heats of formation of the two sulphides it may be safely assumed that the reaction tends to proceed from left to right at lower temperatures, and in the reverse direction at higher temperatures. The reaction constant for this equation is not, however, known.

If either iron or manganese sulphide is soluble in solid steel, its solubility is but small, and a quantitative estimation of this factor is a problem beset with difficulties. Micro-examination as a means of estimating solubility is not a good method, for if the sulphide particles are sub-microscopical in size they remain undetected, but at the same time fall into the category of insoluble material. Further, even visible particles, if they are very small, may easily be confused with other impurities, such as oxide specks.

As a qualitative method, however, micro-examination may be employed, but no great stress must be laid on the results of such an examination. The most desirable method, if it could be used, would be to ascertain the relative solubility of sulphides by a determination of the electrical resistance. Resistivity determinations can be carried out with great accuracy, so far as the physical measurement is concerned, but for the determinations it is essential to provide thin bars of undoubted homogeneity and soundness with respect to constituents other than sulphides, so that differences between various specimens may justly be attributed to an effect of the sulphides, either in or out of solution. Preparation of sound specimens free from blowholes is almost an impossibility when dealing with small amounts of material, and, further, though a specimen might appear to be sound externally, a small blowhole or particle of non-metallic inclusion would affect the electrical resistance to a greater extent than any small variation in dissolved sulphides.

The electrical resistance method, although theoretically most

desirable, presented practical difficulties which could not be overcome. As an exact measurement of even the relative solubility of iron and manganese sulphide seemed impossible, it was decided to employ a qualitative method which would at least indicate whether iron and manganese sulphides were soluble to even a small degree in solid steel.

Experimental Methods Employed.

The experimental method finally adopted by the authors was to determine the effect of iron sulphide and manganese sulphide on the temperature and magnitude of the Ar_3 change in iron.

Melts of Armco iron weighing 130 grm. were made, to which either yellow sulphur or yellow sulphur and manganese in weighed amounts were added. The melting was done in a vertical molybdenum wire-wound furnace similar in type to that described in Section II., and alundum crucibles were used. The crucibles, which were small, measured approximately 4 in. \times 1½ in. externally; they were round, and had a bore of about 1 in. No carborundum was used, so that the melt was completely decarburised by the hydrogen gas used as the protective medium for the molybdenum wire.

After the sulphur and manganese had been added to the molten iron, the additions being made without withdrawing the crucible from the furnace, the melt was allowed to heat up to a high temperature before pouring; it was, of course, well stirred (with an alundum stirrer). About half of the melt was cast in a small chill mould, which on being filled was immediately plunged into cold water to effect as rapid cooling as possible, and the remainder of the still molten alloy contained in the crucible was replaced in the furnace, where it solidified after about 30 sec. It was then allowed to cool down with the furnace.

On analysing the slowly cooled and chilled portions, it was found that whilst the analyses of the two were the same, there was a loss of manganese amounting in some cases to half that added. In view of the fact that the metal had been melted in a reducing atmosphere, this was surprising. If the temperature of the furnace were raised so as to retain the metal put back in the furnace in a molten state for several minutes, a further loss

occurred, so that what amounted to a remelting of the metal remaining in the crucible had to be avoided. In this manner two specimens were made from each melt, one representing the rapidly cooled and the other the slowly cooled state.

Small sections of uniform size were cut from the chilled and slowly cooled specimens, and cooling curves were taken. All curves were taken *in vacuo*, and a platinum/platinum-rhodium couple was used throughout.

Iron-Sulphur Alloys.

Two series of examples showing the types of curves obtained with iron-sulphur alloys are given in Figs. 22 and 23. Fig. 22 is a series of curves obtained with an iron-sulphur alloy containing 0.35 per cent. of sulphur. The first seven curves are of the chilled specimen, curve 1 being of the specimen in its originally chilled state, and 2 to 7 representing the effect of continued heating and cooling. The initial temperature and time of soaking is given at the top of each curve. The slowly cooled state is represented by curve 8, whilst a curve of Armco iron is included for comparison (curve 9). As a means of comparison the temperature of the maxima of the Ar_3 will be used.

The points of interest in these curves are as follows: In the "as quenched" state the temperature of the maximum of the Ar_3 is lower than that of Armco iron by $15^{\circ}C.$, whilst the magnitude of the heat evolution is very considerably less. On continuously heating and cooling, there is a slight rise in temperature of the maximum, and a small increase in the magnitude of the heat evolution. Whether the alloy be soaked above or below the Fe-FeS eutectic point, which occurs at about $1000^{\circ}C.$, makes but little difference in the form of the curve. Further, even after the seventh heat, the curve does not coincide with that of the slowly cooled specimen, either with respect to the maximum temperature or the magnitude of the point. The slowly cooled state produced a smaller evolution of heat and a maximum at a lower temperature than Armco iron.

The alloys forming the second series (Fig. 23) contained 0.5 per cent. of sulphur. Curve 1 is of the "as quenched" specimen, and Nos. 2 to 5 are curves taken after repeated

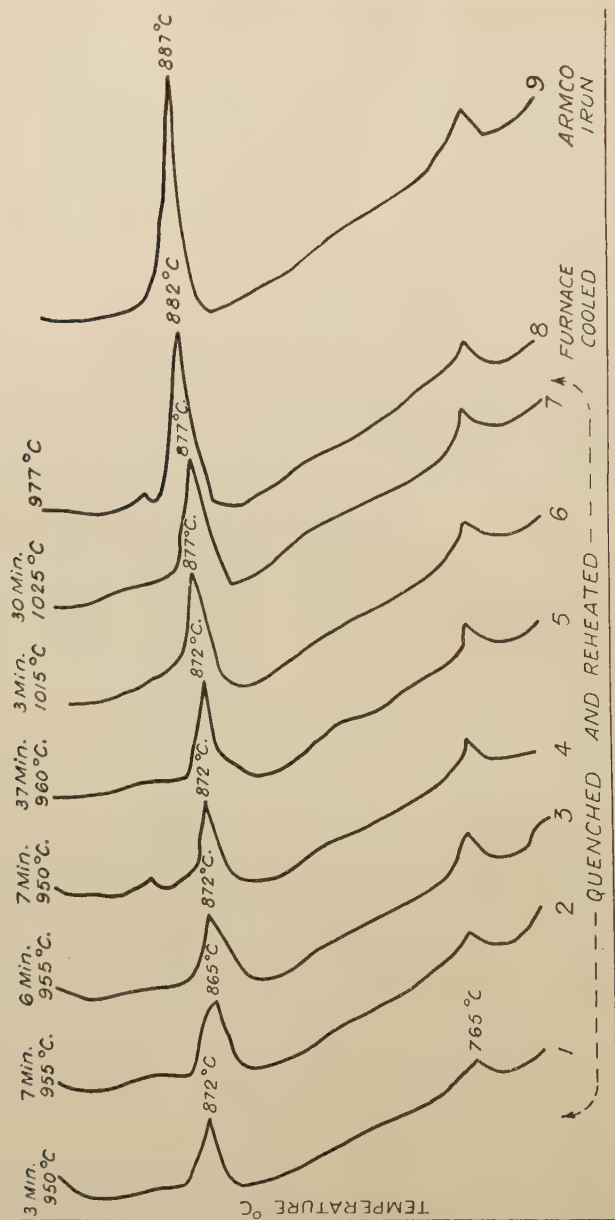


FIG. 22.—Iron-Sulphur Alloy. S = 0.35 per cent.

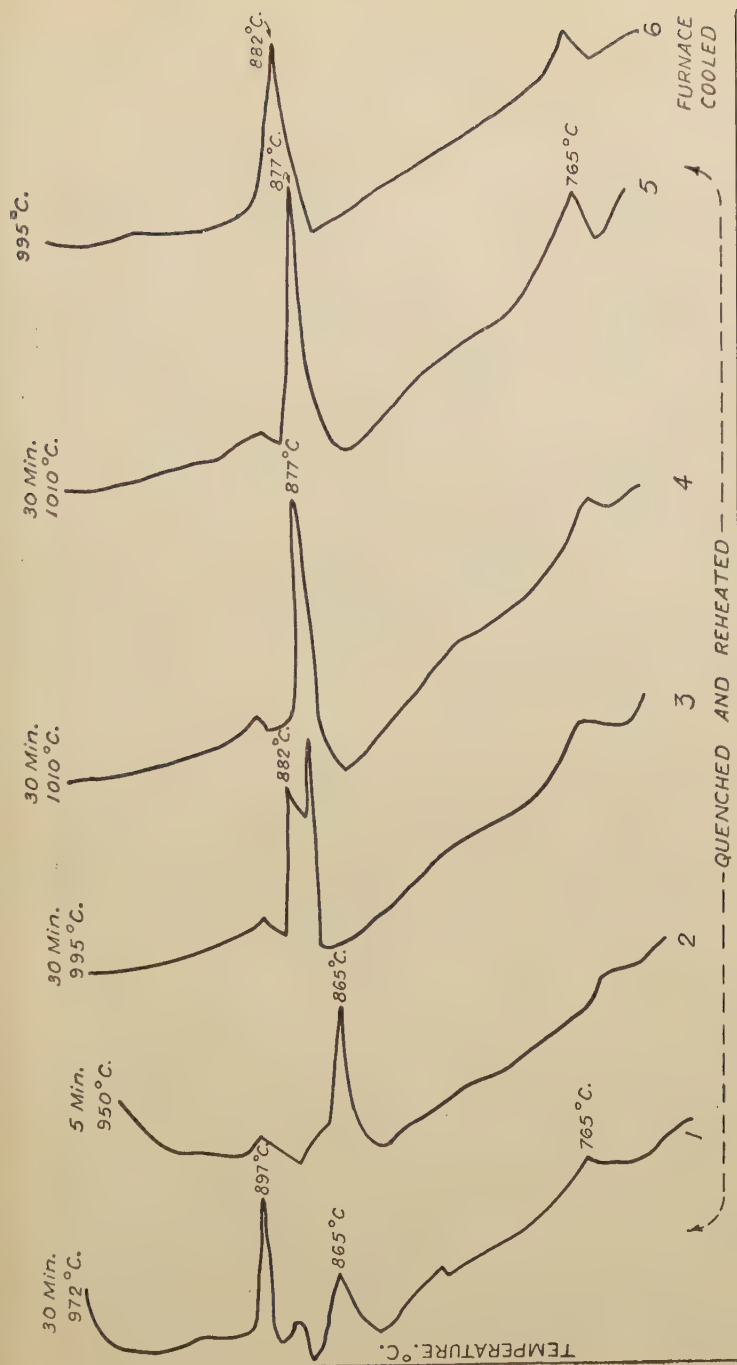


FIG. 23.—Iron-Sulphur Alloy. S = 0.5 per cent.

heatings to the temperatures given. No. 6 represents the slowly cooled state.

It is evident that a greater quantity of sulphur has been retained in solution in this series as compared with the former. Curve 1 shows a multiplicity of points, which after a further heating are smoothed out into two definite evolutions, one at 897°C . and a larger one at 865°C . In curve 3 the lower one has been raised, whilst there is an indication of a small point at about 897°C . In curve 4, whilst the two larger points in curve 3 become merged into one, the small upper point still persists. Curve 5 is similar to curve 4, and shows a partial but not complete return to the normal. The slowly cooled specimen gave a curve very similar to that obtained in the previous series.

In both series what is regarded as the magnetic change occurs at 765°C ., and remains unchanged by the various treatments.

These curves would seem to show conclusively that sulphur may be retained in solution to an appreciable amount by rapidly cooling the melt, and, further, even in the case of a slowly cooled melt, there is evidence of the retention of a small amount of sulphur in solution. No attempt to explain the significance of the innumerable points shown in curve 1 (Fig. 23) will be made; whether they are all due to the deposition of FeS , to the actual formation of FeS , or to a change in the allotropic condition in the iron, cannot even be guessed at. Any attempt to quench between the various points would be futile, for, on account of their change in magnitude and position with repeated heatings, such a method of attack would be invalid.

Iron-Manganese-Sulphur Alloys.

Whilst many melts of the ternary alloys were made, only two series will be dealt with. Fig. 24 represents curves taken with an alloy containing 1.4 per cent. of manganese and 0.31 per cent. of sulphur. Curve 1 is of the specimen in the "as quenched" condition, and curves 2 to 7 were taken after heating the same specimen to the temperatures indicated. Curves 8 and 9 are of the slowly cooled specimen, curve 9 being added merely to show that no difference in form is evident after a second heating.

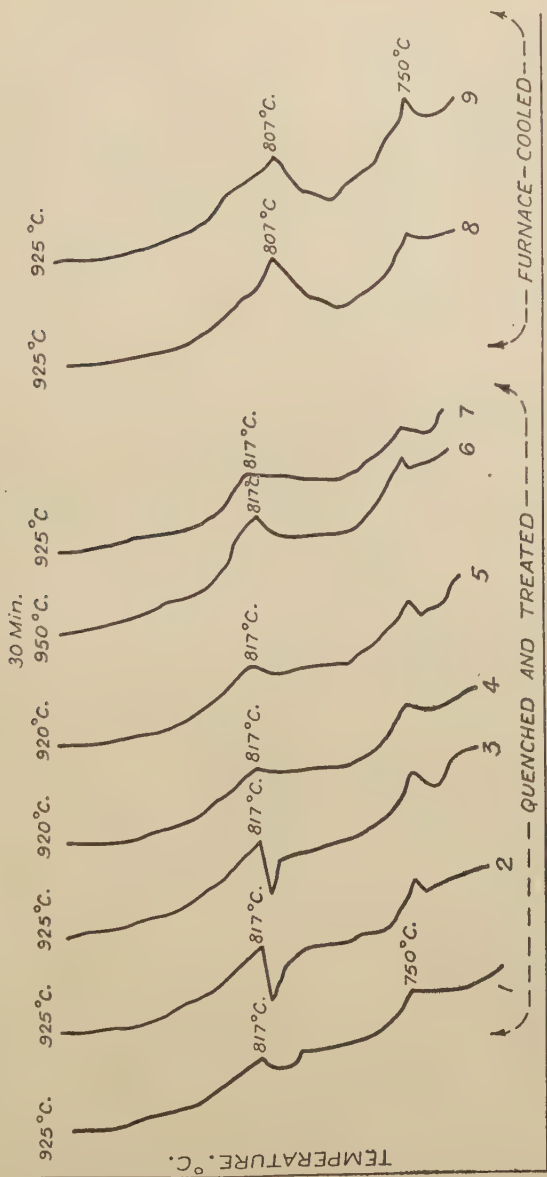


Fig. 24.—Iron-Manganese-Sulphur Alloy. Mn = 1.4 per cent., S = 0.31 per cent.

The peculiar feature of these curves lies in the obvious absorption of heat which follows upon the evolution of heat at 817° C. (curves 1, 2, and 3). Whilst the temperature of the maximum of the Ar_3 is the same in all curves of the quenched specimens, the magnitude of the evolution increases in a marked degree after repeated heatings, whilst if the curve of the "as quenched" specimen be compared with that of the slowly cooled piece the difference in the magnitude is striking. Another very peculiar feature of these curves is that the maximum of the point in the curve of the slowly cooled specimen is at a lower temperature than that of the corresponding quenched condition by 10° C.

A further series, in which the manganese content was 1.3 per cent. and the sulphur 0.26 per cent., is shown in Fig. 25. Curves 1 and 2 are of specimens in the "as quenched" condition, curve 2 following immediately upon curve 1. These represent specimens quenched from the liquid at the highest temperature obtainable. Curve 3 is of a specimen which had been quenched just on the point of solidification, whilst curve 4 is of a similar specimen taken from the same sample, but which had been aged for 6 weeks at ordinary temperatures. Curves 5, 6, and 7 are of similar aged specimens, 5 being the first heating, and 6 and 7 subsequent heatings. Curve 8 is of a specimen in the slowly cooled state, and curve 9 is of a similar specimen taken from the same small ingot after ageing for 6 weeks.

Curves 1 and 2, in Fig. 26, represent specimens of an iron-manganese alloy containing 1.55 per cent. of manganese and no sulphur, quenched and slowly cooled, respectively.

The curves for the iron-manganese-sulphur alloys possess some peculiar features, and, whilst it is impossible to make any definite deductions from them, the following features may be worth commenting upon :

(1) As a general rule, curves for the quenched specimens gave a critical point of less magnitude than the corresponding slowly cooled specimens, provided that the quenching from the liquid was carried out at a high temperature.

(2) The slowly cooled state gave rise to a critical change at a slightly lower temperature than the corresponding quenched state.

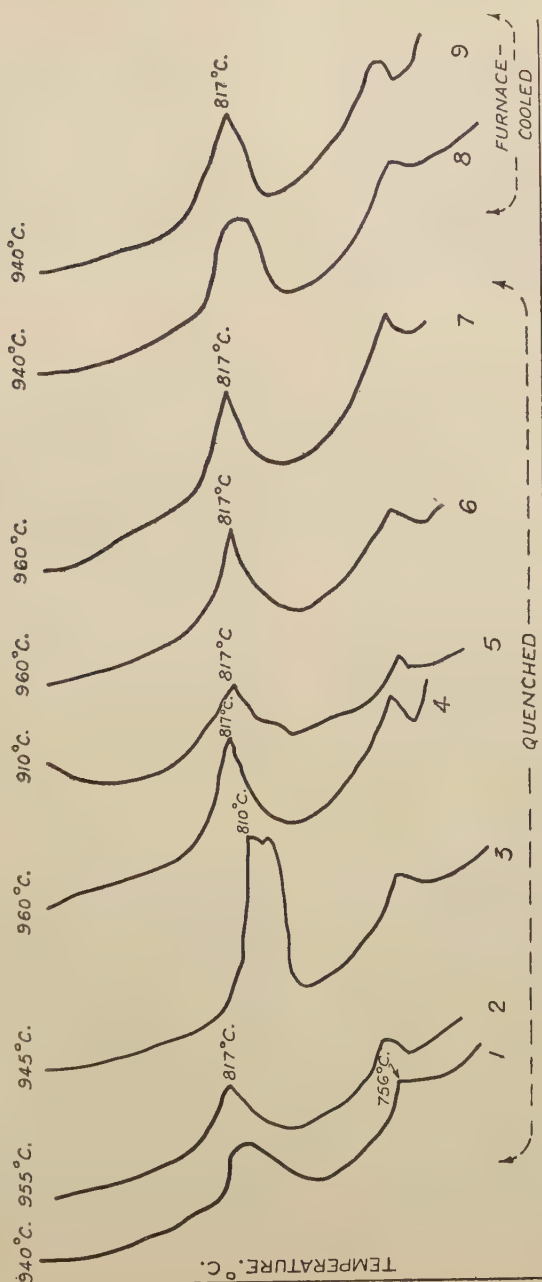


FIG. 25.—Iron-Manganese-Sulphur Alloy. Mn = 1.3 per cent., S = 0.26 per cent.

(3) On quenching from a temperature just above the solidifying point the curve obtained corresponded more with that of the slowly cooled state rather than with that of the quenched condition.

(4) A comparison of the curves taken immediately after the alloys were made and those taken with specimens cut from the same section, but which had been allowed to remain at atmos-

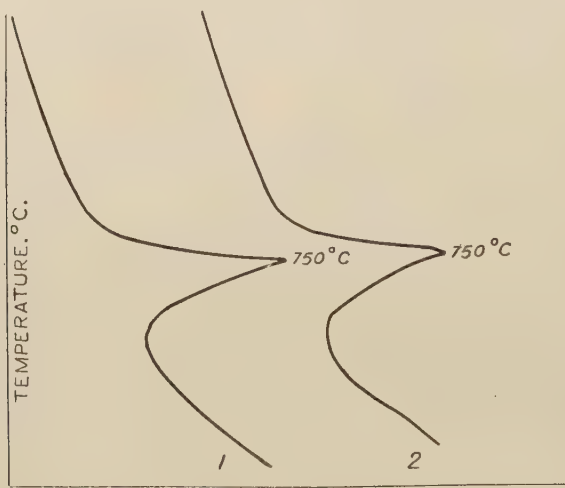


FIG. 26.—Manganese-Iron Alloy. Mn = 1.55 per cent.

pheric temperature for 6 weeks, shows that a change was produced which is reflected in the curves.

(5) If the curves for the iron-manganese alloy containing 1.55 per cent. of manganese be compared with the sulphur-iron-manganese alloys, and allowance be made for the manganese retained by the sulphur in the latter mixtures, it will be seen that the critical points correspond to a normal lowering by the manganese not in combination with the sulphur. The assumption is made that the lowering of A_{r_3} by manganese is linear for the small amounts under consideration.

From the standpoint of the critical point temperatures it would appear that MnS is insoluble in iron, but some doubt is cast on this by the effect of MnS in restraining the evolution

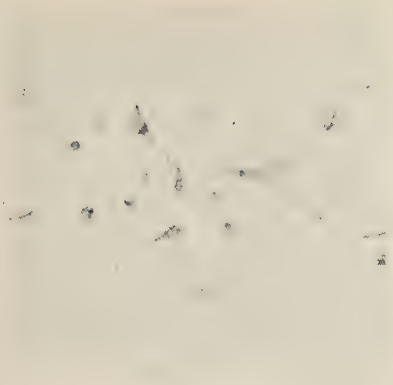


FIG. 27.—Iron-sulphur alloy. Slowly cooled.

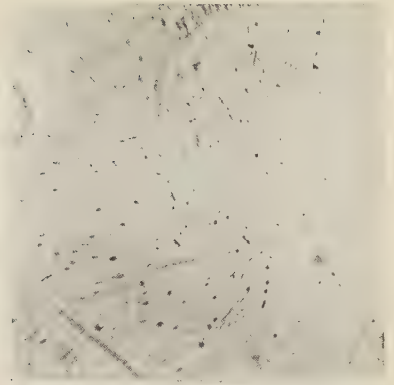


FIG. 28.—Iron-sulphur alloy. Chilled.

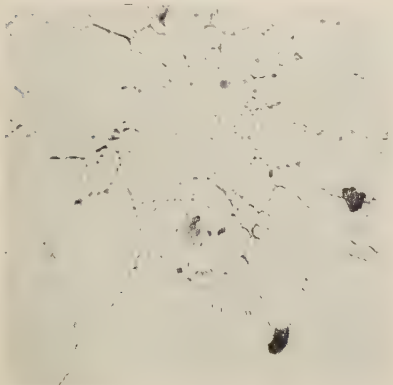


FIG. 29.—Iron-sulphur alloy, showing effect of continued heatings.

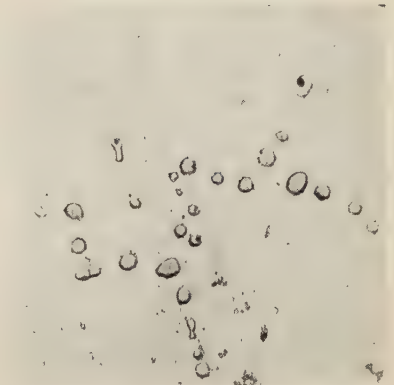


FIG. 30.—Iron-manganese-sulphur alloy. Slowly cooled.



FIG. 31.—Iron-manganese-sulphur alloy. Chilled. Unetched.



FIG. 32.—Iron-manganese-sulphur alloy. Chilled. Lightly etched.

(Magnification, 300 diam. Reduced in reproduction to eight elevenths.)

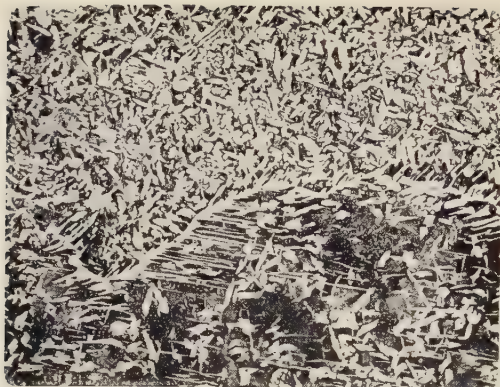


FIG. A.—Structure, similar to the authors' Fig. 10, taken from the interior of an ordinary test-bar casting.



FIG. B.—Angular structure in steel as cast, with one spot "feathery."

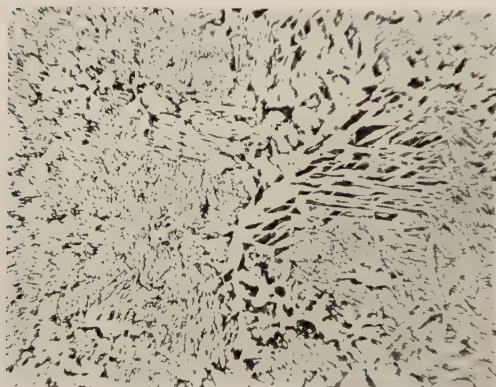


FIG. C.—Feathery structure in steel as cast, with a little angular structure.

Magnification $\times 50$. Reduced in reproduction to five-sevenths.

[To face p. 357.]

—that is, in decreasing the magnitude. The experiments do, however, point to the sulphide being in the form of MnS.

The fact that rapidly chilling the alloys from the melt has the effect of slightly raising rather than lowering the critical change suggests the possibility of MnS being slightly more soluble in δ -iron than in the γ state. On slowly cooling, the alloy would pass slowly from the δ to the γ state, and more opportunity for the δ form to dissolve the sulphide would be allowed. Further, the effect of ageing, which is to raise the critical change, also suggests the very unlikely possibility that solution in the α state, which is the same as the δ in its space-lattice configuration, may have occurred. Experiments are now being conducted to effect a solution of the MnS by heating for a prolonged time at a temperature below that of the critical change.

In selecting the composition of the alloys the authors were guided by the following considerations: Sufficient sulphur must be added to enable its effect to be indicated on the curves. The manganese content must be adjusted so as to more than suffice for the formation of MnS, but at the same time the amount must not be sufficient to lower the critical points to a temperature at which they became too sluggish. In one case, in which an alloy was made containing over 2.5 per cent. of manganese, two distinct critical changes resulted. This alloy was neglected, as it only added difficulties to the problem. Again, if insufficient manganese was added the critical points would too nearly coincide with that of Armco iron, and the amount of sulphur that could be added would be too small for experimental purposes.

Microstructures.

Whilst micro-examination, as has been said, is not a reliable method of ascertaining the amount of sulphide in or out of solution, it may be of interest to include typical examples of microstructures obtained under different conditions of treatment.

Fig. 27 (Plate XL.) represents the type of structure obtained with the slowly cooled iron-sulphur alloys, and Fig. 28 shows an alloy of the same composition in the "as chilled" condition. Fig. 29 indicates the effect of continued heatings on the chilled alloy. It is clear from these micrographs that sulphur can be

retained in solution, and is deposited from solution on heating to above the critical temperature.

Fig. 30 is of an iron-manganese-sulphur alloy, containing 1.3 per cent. of manganese and 0.26 per cent. of sulphur, in the slowly cooled state. Fig. 31 illustrates an unetched section of an alloy of the same composition in the "as chilled" state, and Fig. 32 is the same alloy lightly etched.

Conclusions.

It has been definitely shown that sulphur may be retained in solution in an iron-sulphur alloy by rapidly chilling the melt, and that deposition of sulphide of iron occurs on reheating the alloy to a temperature above 900° C.

With respect to similar work on manganese-iron-sulphur alloys, the results are too indefinite to warrant any specific conclusion, but they do seem to show that manganese sulphide, if it is at all soluble in solid iron, is only very slightly so.

SECTION IV.—INTERIM REPORT ON THE DENSITY OF MOLTEN STEEL.

By PROFESSOR CECIL H. DESCH, F.R.S., and B. S. SMITH, M.Met.
(Carnegie Scholar) (Sheffield).

THE Heterogeneity Committee having considered that a knowledge of the density and viscosity of molten steel and of their variation with temperature is necessary for a complete understanding of the process of solidification, arrangements were made for this work to be undertaken in the Metallurgical Department of the University of Sheffield. Apart from a few early experiments by rough methods, the only previous determinations of the density of steel in the liquid state are those conducted in the laboratory of Professor Benedicks by D. W. Berlin.¹ The method used in the Stockholm laboratory consisted in comparing the height of a column of the liquid metal with that of a column of mercury supporting the same gaseous pressure, and great ingenuity was

¹ C. Benedicks, D. W. Berlin, and G. Phragmén, *Iron and Steel Institute, Carnegie Scholarship Memoirs*, 1924, vol. xiii. p. 129. D. W. Berlin, *ibid.*, 1926, vol. xv. p. 1.

shown in the construction of U-tubes of refractory material capable of retaining the metal and at the same time supporting the requisite pressure of nitrogen or other inert gas. For the present investigation it was decided to use an entirely different method, partly in order to obtain an independent series of determinations, and also with a view to gaining experience which would be useful in the subsequent determination of the viscosity. The Archimedean principle was adopted, a sinker attached to one arm of a balance being weighed in air, mercury, and liquid iron or steel respectively. As it is intended to determine the viscosity by means of a torsional pendulum, the furnace may be made to serve for both series of experiments, whilst the construction of the pendulum may be quite similar to that of the sinker.

In the construction of the furnace, which is of the vertical tube form, wound with molybdenum wire protected by an atmosphere of mixed nitrogen and hydrogen (cracked ammonia), much assistance was given by Dr. C. Sykes. The construction is shown in Fig. 33. Two concentric tubes of alundum with internal diameters 12.5 and 7.5 cm., respectively, are used, the height of the inner tube being about 60 cm., and of the outer 50 cm. The molybdenum winding is on the inner tube, and is protected by the outer one from contact with the refractory material used for heat insulation. Commercial tubes of alundum were used at first, but they have since been made successfully in the laboratory, and the authors are indebted to Professor Andrew for communicating his experience in the preparation of such tubes. The enclosing case is of steel, and the heat-insulating packing is of Sil-o-cel or of crushed sillimanite, the former being much more effective, but sometimes giving trouble owing to its hygroscopic character. It is essential that all moisture should be driven out before the molybdenum wire reaches redness, or its destruction is very rapid. The gas inlet for the leading-in of the stream of gas from the cracking and drying train is in the head of the apparatus, constructed of steel tube with a screwed cap. The exit tubes are at the lower end, gas being taken from two points in the outer packing and also from the base of the inner tube. The tungsten-molybdenum thermocouple passes through the head, which is also provided with an observation

window. The alundum crucible containing the metal is supported on a vertical pillar of sillimanite.

The construction of the sinker is shown in Fig. 34. It was at first intended that the actual sinker should be of metallic tungsten, but it did not appear that any adherent coating could be found which would protect the tungsten from attack by the molten steel. Quite recently some success has been obtained in this direction, and experiments with a metallic sinker are now being made. The construction of the torsional pendulums used by Thielmann and Wimmer¹ is rather more elaborate than is necessary for the density experiments, and after many trials it was decided to use alundum cylinders for this purpose. The suspending rod is of tungsten, and its lower end is protected by a short length of alundum tubing, around which the alundum cylinder is moulded. Each cylinder is thoroughly fired at 1650° C. before being used. As its density is too low to allow it to sink in the steel, it has to be weighted, and this has been done by attaching a rectangular box of molybdenum sheet, weighted with the necessary quantity of solid tungsten. The depth of immersion is regulated by the two molybdenum wires shown in the figure, which are bent at right angles and touch the liquid surface at their pointed ends. The tungsten rod is attached to a steel rod by means of a sleeve and two screws at such a height that the temperature is not excessive, and this steel suspension is interrupted by a right- and left-handed screw connection below the balance-pan so that the height may be readily adjusted. The balance, with a hole in the case below one of the pans, is supported on a frame over the furnace.

When carrying out an experiment, the air is thoroughly expelled from the apparatus after the crucible has been placed in position. The sinker, the weight of which in air has been determined, is supported above the level of the crucible during heating, and the opening through which the suspension rod enters the furnace is closed with fireclay, so that the current of gas shall pass downwards. When the metal is seen to be completely molten and any evolution of gas which may occur has ceased, the fireclay packing round the suspension is removed, the nitrogen-hydrogen mixture then escaping from the opening;

¹ H. Thielmann and A. Wimmer, *Stahl und Eisen*, 1927, vol. xlvii. p. 389.

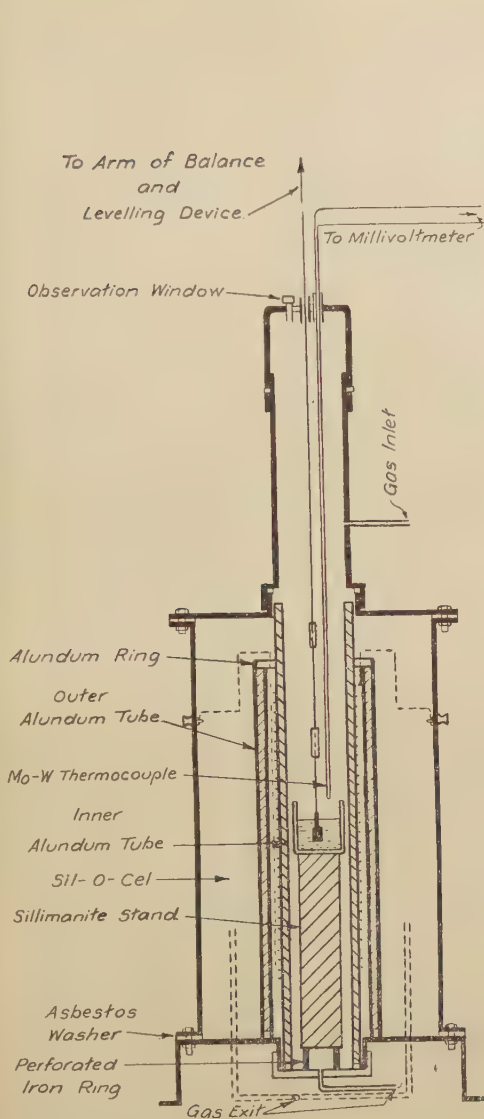


FIG. 33.—Apparatus for the Determination of the Density of Liquid Iron and Steel. (Scale: one-tenth natural size.)

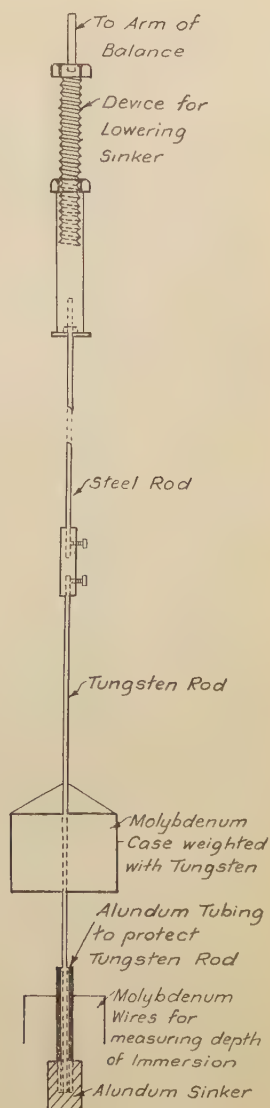


FIG. 34.—Sinker Used in Density Measurements. (Scale: one-quarter natural size.)

the sinker with its levelling device is attached to the arm of the balance, and is lowered until the tips of the levelling wires come into contact with the liquid surface. As this surface is very bright and reflects perfectly, there is no difficulty in recognising the moment when the wires and their reflections just meet. The depth of immersion is then known. Much trouble was caused at first by the tendency of the sinker to be drawn out of the perpendicular and to approach the walls of the crucible. This has to be overcome by gently rotating the sinker in a horizontal plane. It is less serious the lower the centre of gravity of the system, and this is a main reason for the experiments with specifically denser sinkers referred to below. Balance having been obtained by the addition of weights to the opposite pan, a reading is taken, and the sinker is then raised and the thermocouple lowered into the metal for the determination of the temperature. The sheath protecting the thermocouple has usually been of Pythagoras tubing, but success has now been obtained with tubes of zircon, prepared in the laboratory.

After the whole apparatus has been allowed to cool, the current of gas being kept flowing during cooling, the sinker is removed, inspected for flaws, and calibrated by weighing in mercury contained in a crucible of the same size as that used for the high-temperature experiment, the levelling device being used as before. It is then re-weighed in air. The constancy of weight and volume have been found very satisfactory, and some sinkers have been used repeatedly. When the exclusion of oxygen from the furnace has been complete, the sinkers are quite unattacked by the iron, which does not wet the surface.

The correction for the expansion of the alundum is based on the determinations of Norton.¹ The graph showing the relation between the length of a specimen of alundum and the temperature has been determined up to 1580° C. Over the range covered by the experiments with steel the graph is a straight line, and the linear expansion of alundum may be taken as 0.0000077 per degree centigrade. The alundum used in making the sinkers approximated closely in composition and grain-size to that used by Norton.

¹ F. H. Norton, *Journal of the American Ceramic Society*, 1925, vol. viii, p. 799.

In order to lower the centre of gravity of the system, sinkers were made on a different plan. A mixture of tungsten powder with 3 per cent. of alundum was compressed and coated with alundum, and then fired in the furnace in which the sinkers were to be used. Such sinkers proved to be satisfactory, but the results are not included as the coefficient of expansion of the compound mass is unknown. Massive tungsten sinkers protected by an alundum wash were used for the experiments with pig iron at 1350° to 1450° C. At higher temperatures the coating was easily detached, but this difficulty has now been overcome.

The numerical results obtained can only be regarded as preliminary values, but their agreement is sufficiently good to suggest that they are not far from the true values, although greater accuracy will be necessary before the temperature coefficient can be determined with certainty. The alloys with high carbon, prepared by melting Swedish pig iron, were melted in a salamander crucible. The following are some of the values that have been determined :

Carbon Content after Melting. %	Temperature. ° C.	Density.	
0·03	1530	6·79	Alundum sinker
0·04	1545	7·05	
0·04	1560	6·97	
0·04	1550	6·95	
0·04	1545	6·97	
0·04	1550	7·06	
3·38	1300	7·26	Alundum sinker
3·54	1340	7·23	
3·65	1320	7·31	
3·65	1310	7·28	
3·12	1465	7·17	Solid tungsten sinker
3·38	1405	7·23	
3·34	1345	7·32	
3·14	1350	7·23	

For equal temperatures, these results are lower than the final values given by Berlin, but are in good agreement with those contained in the first paper by Benedicks, Berlin, and Phragmén.

The authors would like to express their indebtedness to the Council of the Iron and Steel Institute for having contributed towards the cost of the investigation, and for having awarded a grant of £100 from the Carnegie Research Fund to Mr. Smith.

SECTION V.—THE EFFECT OF LATENT HEAT ON THE SOLIDIFICATION OF STEEL INGOTS.

By N. M. H. LIGHTFOOT, M.A. (Sheffield).

THE following is the outline of an attempt to determine the effect of the liberation of latent heat of fusion on the rate of solidification of steel ingots. A full mathematical discussion has been prepared, and has been accepted by the London Mathematical Society for publication.

The only previous attempts to take account of latent heat which have come to the notice of the author have been made by Saitô¹ and Feild.² Saitô's work does not make direct reference to the latent heat of fusion, but to the latent heat evolved at about 700° C. Within the limitations of the present paper, necessitated by certain simplifying assumptions, the theory of the two cases is identical, and a direct comparison between Saitô's results and those of this investigation is possible. The results of Feild do not agree with those of this paper; some of his assumptions are difficult to follow, as the mathematical reasoning is omitted. As the solutions given below do satisfy all the mathematical conditions required, in the steel and at the boundary, they would appear to be correct, within the limitations mentioned above.

The assumptions made are that the diffusivity κ , the specific heat c , and the density ρ , of the steel are constant for all temperatures, and the same for liquid as for solid steel. In the case in which a mould is considered, these constants are assumed to have the same values for the mould as for the steel. No account is taken of convection currents in the molten metal, nor of the separation of the ingot from the mould. While it is realised that these conditions are far from those obtaining in practice, they do render the mathematical discussion more tractable, and it is hoped that the general effect of latent heat on the cooling process will be evident from the results obtained.

¹ S. Saitô, "On the Distribution of Temperature in Steel Ingots during Cooling," *Science Reports of the Tôhoku Imperial University*, 1921, vol. x. p. 305. (See §§ 10 and 11, and Plate XXIX.)

² Alexander L. Feild, "Solidification of Steel in the Ingot Mould," *Transactions of the American Society for Steel Treating*, 1927, vol. xi. p. 264.

Even with these assumptions it has been found possible to deal with only some of the simplest types of boundary conditions. Those discussed are :

- I. "Semi-infinite" mass of molten steel, originally at constant temperature, the boundary $x = 0$ being always at constant (zero) temperature.
- II. "Semi-infinite" mass, as in I., but placed in contact along the plane $x = 0$ with a semi-infinite mass of steel originally at constant (zero) temperature.
- III. Slab of constant finite thickness, but otherwise of infinite extent, originally at constant temperature, the bounding planes $x = 0$ and $x = a$ being at constant (zero) temperature.

The first two cases have been solved exactly. The solutions will apply approximately near the surface of a cylindrical ingot at the beginning of the process of solidification. Case II. will give a first approximation to the effect of a mould of finite thickness. As soon as the outer surface of such a mould has reached a sufficient temperature for appreciable radiation to take place, the approximation will be no longer valid. Case III. has been solved only approximately, but gives an indication of the velocity of the wall of solidification when it reaches the centre of the ingot, and can be compared with Saitô's result,¹ which is obtained by graphical approximation.

In each of the above cases, any plane parallel to the plane $x = 0$ will be an isothermal plane, and the wall of solidification will be a plane at constant temperature, separating the liquid from the solid steel, and moving in a direction perpendicular to itself. As the plane advances, latent heat will be evolved owing to the solidification of the molten steel. This heat must be conducted away, and this necessitates a discontinuity in the temperature gradient at the plane concerned.

If the position of the plane of solidification be assumed to be given at any time t by the equation

$$x = f(t),$$

¹ *Loc. cit.*

and if v_1 and v_2 are the temperatures in the solid and liquid steel respectively, both being functions of both x and t , the conditions to be satisfied are :

- (α) v_1 and v_2 must both satisfy the equation of conduction ¹—namely,

$$\frac{\partial v}{\partial t} = \kappa \frac{\partial^2 v}{\partial x^2} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

- (β) v_1 must satisfy the conditions at the boundary $x = 0$, and v_2 must satisfy the initial conditions, when $t = 0$.
 (γ) At the moving plane of solidification the rate of evolution of heat must be exactly equal to the rate at which heat is conducted away from the plane—that is,

$$\kappa c \rho \left[\frac{\partial v_1}{\partial x} - \frac{\partial v_2}{\partial x} \right]_{x=f(t)} = \lambda \rho f'(t). \quad . \quad . \quad . \quad (2)$$

where λ is the latent heat of fusion. The left-hand side of equation (2) represents the rate at which heat is conducted from unit area of the plane $x = f(t)$,¹ and the right-hand side the rate of evolution of latent heat per unit area.

- (δ) v_1 and v_2 must be continuous, though their space gradients are discontinuous at the plane of solidification, and if V is the freezing temperature, the equations

$$v_1 = v_2 = V$$

must hold when $x = f(t)$ is substituted in the expressions for v_1 and v_2 .

These conditions are theoretically sufficient to determine v_1 , v_2 , and the function $f(t)$. The solutions which have been obtained in cases I. and II., and the approximate solution in case III., are now given.

Case I. “Semi-infinite” mass of molten steel, originally at constant temperature, the boundary ($x = 0$) being kept at constant (zero) temperature.—The original constant temperature of the molten steel is taken as Φ , and the freezing temperature V . The plane $x = 0$ is constantly at zero temperature.

¹ Carslaw, “The Conduction of Heat.”

latent heat is neglected is the square of the ratio of the values of k found from equations (5) and (6) respectively.

As a numerical illustration the following values of the constants were taken¹:

$$\begin{aligned}\Phi &= 1600^\circ \text{C.} \\ V &= 1500^\circ \text{C.} \\ \lambda &= 48 \text{ cal. per grm.} \\ c &= 0.12. \\ \kappa &= 0.0974.\end{aligned}$$

The value of k obtained from equation (5) is 0.893, and that from equation (6) is 1.317. Thus, the ratio of the actual speed at any point to the speed calculated when latent heat is neglected is, in this case,

$$\left(\frac{0.893}{1.317}\right)^2 = 0.46.$$

This ratio shows the importance of the effect of latent heat.

The temperature distributions near the boundary at different times, calculated from equations (4), are shown graphically in Fig. 35, and the corresponding curves when latent heat is neglected in Fig. 36. The position of the plane of solidification at any time is shown in Fig. 37, curve *A*, and the position when latent heat is neglected in Fig. 37, curve *B*.

Case II. “Semi-infinite” mass of molten steel, originally at constant temperature, placed in contact at the plane $x = 0$ with a semi-infinite mass of steel originally at constant (zero) temperature.—The initial conditions are

$$v = 0, \text{ for } x < 0,$$

and

$$v = \Phi, \text{ for } x > 0.$$

The solution is

$$\begin{aligned}f(t) &= 2k\sqrt{\kappa t} \\ v_1 &= \frac{V}{1 + \Theta(k)} \left\{ 1 + \Theta\left(\frac{x}{2\sqrt{\kappa t}}\right) \right\} \\ v_2 &= \frac{V - \Phi\Theta(k)}{1 - \Theta(k)} + \frac{\Phi - V}{1 - \Theta(k)} \Theta\left(\frac{x}{2\sqrt{\kappa t}}\right) \end{aligned} \quad (7)$$

where now

$$V = \left\{ 1 + \Theta(k) \right\} \left\{ \frac{\Phi}{2} + \frac{\sqrt{\pi}}{2} \cdot \frac{\lambda k}{c} e^{k^2} [1 - \Theta(k)] \right\} \quad (8)$$

¹ These values were suggested by Mr. J. Woolman, of the Brown-Firth Research Laboratories, Sheffield, to whom the author is indebted for much valuable practical information.

It is easily proved, as before, that the initial and boundary conditions are satisfied. It should be noted that if x is negative,

$$\Theta\left(\frac{x}{2\sqrt{\kappa t}}\right) \rightarrow -1 \text{ as } t \rightarrow 0, \text{ giving } v_1 = 0 \text{ when } t = 0.$$

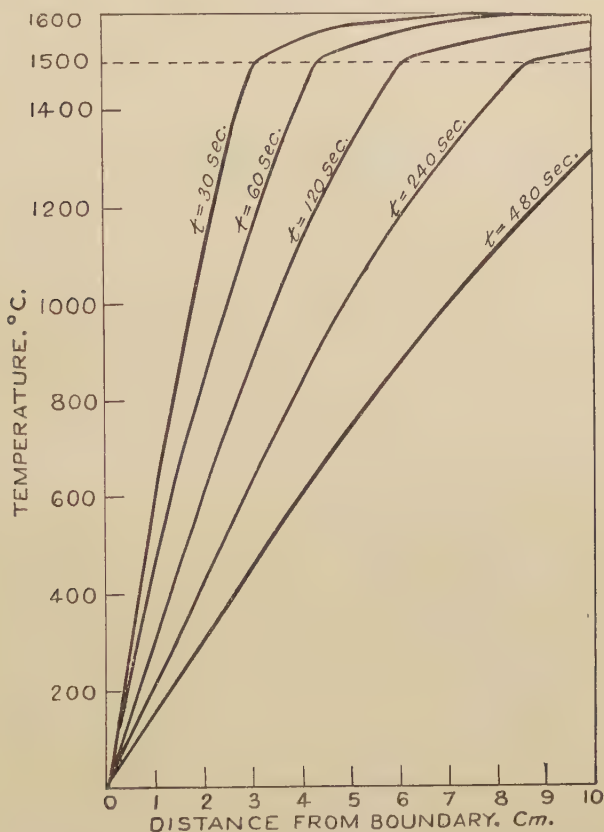


FIG. 35.

Using the same numerical values as in case I., it is found from equation (8) that

$$k = 0.6265.$$

The temperature distributions for the same times as in case I. are shown in Fig. 38 (p. 372).

This is the problem investigated by Feild,¹ in the particular case of $\Phi = V$, or when the steel is originally just at the freezing point. It should be noted that in this case equation (7) gives $v_2 = V$ for all values of x and t , as was to be expected.

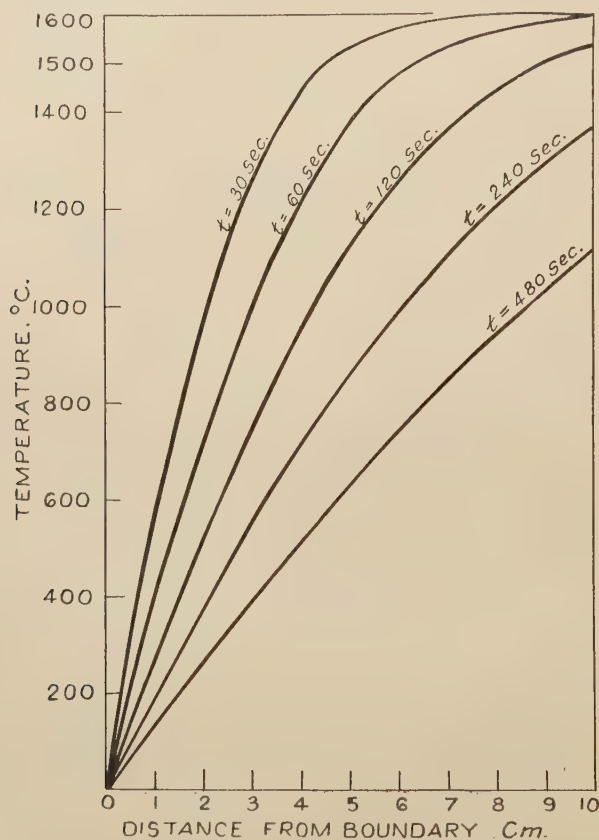


FIG. 36.

The numerical values used by Feild are :

$$\begin{aligned}
 V &= \Phi = 1500^{\circ} \text{C.} \\
 \lambda &= 70, \\
 c &= 0.15, \\
 \text{thermal conductivity, } K &= 0.07 = \kappa c \rho, \\
 \rho &= 7.5.
 \end{aligned}$$

¹ *Loc. cit.*

With these values it is found that

$$k = 0.682.$$

Thus, the position of the wall of solidification at time t is,

$$\begin{aligned} x &= 2k\sqrt{\kappa t} \\ &= 0.34\sqrt{t}. \end{aligned}$$

The value obtained by Feild is

$$x = 0.88\sqrt{t}.$$

It should be noted that Feild makes the same assumptions as to the physical conditions as are made in this paper.

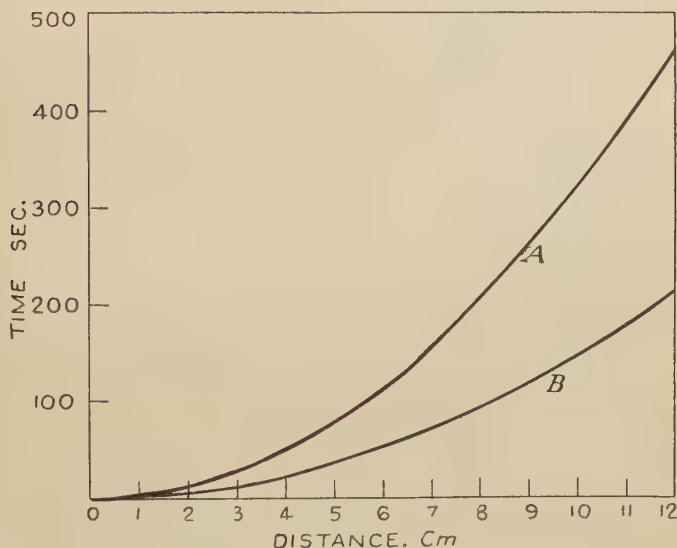


FIG. 37.

Case III. Slab of constant finite thickness, but otherwise of infinite extent, originally at constant temperature, the boundary planes ($x = 0$ and $x = a$) being kept at constant (zero) temperature.—The initial and boundary conditions assumed are

$$\begin{aligned} v &= \Phi, \text{ when } t = 0, 0 < x < a, \text{ and} \\ v &= 0 \text{ at } x = 0 \text{ and } x = a, \text{ for all values of } t. \end{aligned}$$

It has not been found possible to obtain an exact solution in this case, except for the particular value of the initial temperature

$\Phi = V$. In this case there is no temperature gradient in the liquid, and solidification proceeds from each of the boundaries

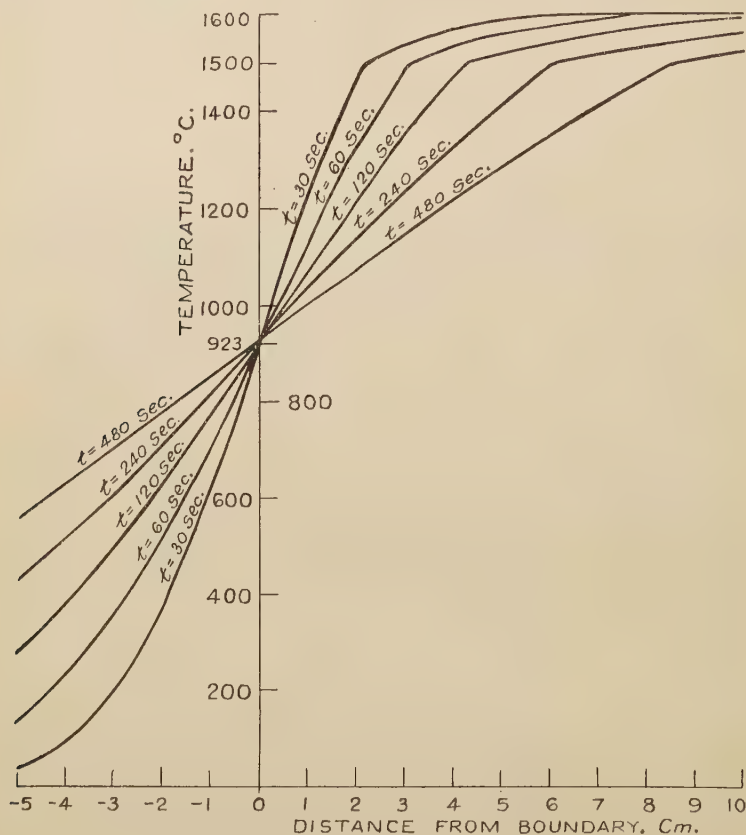


FIG. 38.

independently, until the process is completed. The solution in this particular case is

$$f(t) = 2k\sqrt{\kappa t}$$

$$V = \sqrt{\pi} \frac{\lambda k}{c} e^{k^2} \Theta(k)$$

$$v_1 = \frac{V \Theta\left(\frac{x}{2\sqrt{\kappa t}}\right)}{\Theta(k)}, \text{ when } x < 2k\sqrt{\kappa t}$$

$$v_2 = V, \text{ when } 2k\sqrt{\kappa t} < x < a - 2k\sqrt{\kappa t}$$

$$v_1 = \frac{V \Theta\left(\frac{a-x}{2\sqrt{\kappa t}}\right)}{\Theta(k)}, \text{ when } a - 2k\sqrt{\kappa t} < x < a.$$

The reason for the two separate expressions for v_1 is that there are now two moving planes of solidification, given by

$$x = 2k\sqrt{\kappa t} \text{ and} \\ x = a - 2k\sqrt{\kappa t}.$$

Again it is easily verified that this solution satisfies all the required conditions, initially and at the fixed and moving boundaries.

In the more general case only an approximate solution has been obtained. If it be taken that

when $0 < x < 2k\sqrt{\kappa t}$,

$$v_1 = \frac{V\Theta\left(\frac{x}{2\sqrt{\kappa t}}\right)}{\Theta(k)} + \frac{\Phi - V}{1 - \Theta(k)} \sum_{n=1}^{\infty} (-1)^n \left\{ \Theta\left(\frac{ma + x}{2\sqrt{\kappa t}}\right) - \Theta\left(\frac{ma - x}{2\sqrt{\kappa t}}\right) \right\} \quad \left. \begin{array}{l} \text{and when } 2k\sqrt{\kappa t} < x < a - 2k\sqrt{\kappa t}, \\ v_2 = \frac{V - \Phi\Theta(k)}{1 - \Theta(k)} + \frac{\Phi - V}{1 - \Theta(k)} \left[\Theta\left(\frac{x}{2\sqrt{\kappa t}}\right) + \sum_{n=1}^{\infty} (-1)^n \left\{ \Theta\left(\frac{ma + x}{2\sqrt{\kappa t}}\right) - \Theta\left(\frac{ma - x}{2\sqrt{\kappa t}}\right) \right\} \right] \end{array} \right\} \quad (9)$$

where the temperature when $a - 2k\sqrt{\kappa t} < x < a$ is deduced from the expression for v_1 by substituting $(a - x)$ in place of x , and where $f(t)$ and k are given by equations (3) and (5) respectively, it is found that all the conditions except (8) are satisfied; the temperature at the plane where $x = 2k\sqrt{\kappa t}$ is not equal to the freezing temperature, but to

$$V + \frac{\Phi - V}{1 - \Theta(k)} \sum_{n=1}^{\infty} (-1)^n \left\{ \Theta\left(\frac{ma}{2\sqrt{\kappa t}} + k\right) - \Theta\left(\frac{ma}{2\sqrt{\kappa t}} - k\right) \right\} \quad (10)$$

If, however, t is small the variable part of the expression (10) is very small, and it is found that with the same numerical values as in case I. the temperature at the plane given by $x = 2k\sqrt{\kappa t}$ differs from 1500°C. by less than about 17°C. , until this plane reaches the position $x = \frac{3a}{8}$. Thus, until this stage is reached a very good approximation to the temperature is given by equations (9).

After this stage is reached, the discrepancy becomes rapidly more serious, and in order to get a fairly close approximation, it

is necessary to assume a different form for $f(t)$. The expressions for the temperature become very complicated, and can only be given in terms of a constant, the value of which must be adjusted in any particular numerical case so as to make the temperature at the plane of solidification as nearly as possible constant.

It is found that for the same numerical values as in case I. the position of the moving solid boundary at any time t is given approximately by

$$x = 1.786\sqrt{\kappa t}, \text{ for } 0 \leq x \leq \frac{3a}{8}, \text{ and}$$

$$x = 3.639a - 5.290\sqrt{0.4275a^2 - \kappa t}, \text{ for } \frac{3a}{8} \leq x \leq \frac{a}{2}.$$

The expressions for the temperature are not given because of their extreme complexity, nor has the temperature distribution been calculated for this case because the arithmetical labour involved is enormous, but it has been verified that all the conditions required are satisfied, except that the temperature at the plane of solidification is not exactly 1500°C. , but differs from this value by not more than about 1.5 per cent. for any value of t . Thus, the above approximation may be taken to represent with considerable accuracy the position of the wall of solidification at any time. Fig. 39, curve *A*, shows this position graphically, and Fig. 39, curve *B*, shows the corresponding relation when latent heat is neglected. The entirely different character of the two curves near the central plane of the slab should be noted. It is evident that as the plane of solidification approaches the central plane its velocity is practically constant, while in the case where latent heat is neglected this velocity tends to infinity at the central plane.

The method has also been applied to the case discussed by Saitô,¹ in connection with the heat evolved at 700°C. The numerical values used by him are

$$\begin{aligned}\Phi &= 850^\circ \text{C.} \\ V &= 700^\circ \text{C.} \\ a &= 20 \text{ cm.} \\ \kappa &= 0.0974. \\ \lambda &= 18.2. \\ c &= 0.12.\end{aligned}$$

¹ *Loc. cit.*

The formulæ giving the approximate position of the plane at the temperature 700°C. , obtained by the author's method, are

$$x = 1.571\sqrt{\kappa t}, \text{ when } 0 \leq x \leq \frac{a}{4}, \text{ and}$$

$$x = 6.926a - 8.12\sqrt{0.7015a^2 - \kappa t}, \text{ when } \frac{a}{4} \leq x \leq \frac{a}{2}.$$

Again it has been verified that at the moving plane given by these formulæ the temperature differs from 700°C. by not more than about 1.5 per cent. for any value of t .

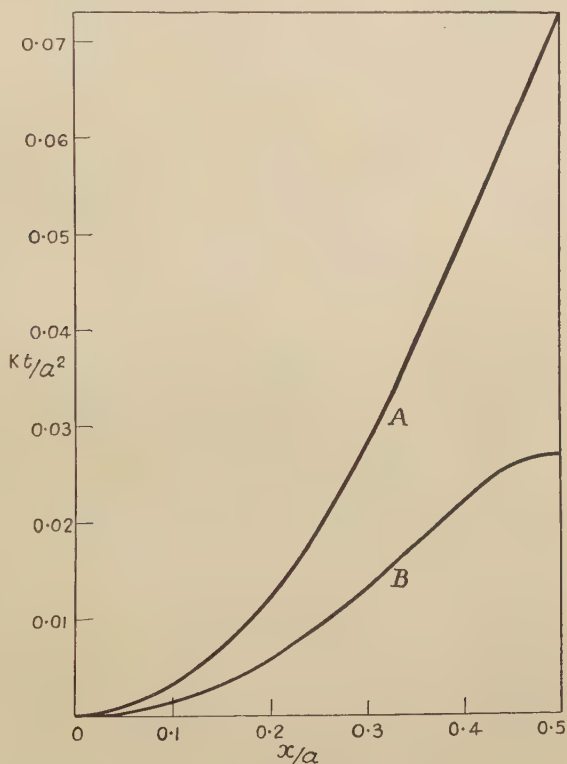


FIG. 39.

The position of this plane at any time is shown graphically by curve *A* in Fig. 40. Curves *B* and *C* are reproduced from Saitô's paper, and show, respectively, his approximation to the

position of the plane when latent heat is taken into account, and the position of the plane when latent heat is neglected. It should be observed that his graphical approximation tends to verify the results of this paper. It seems likely that had he

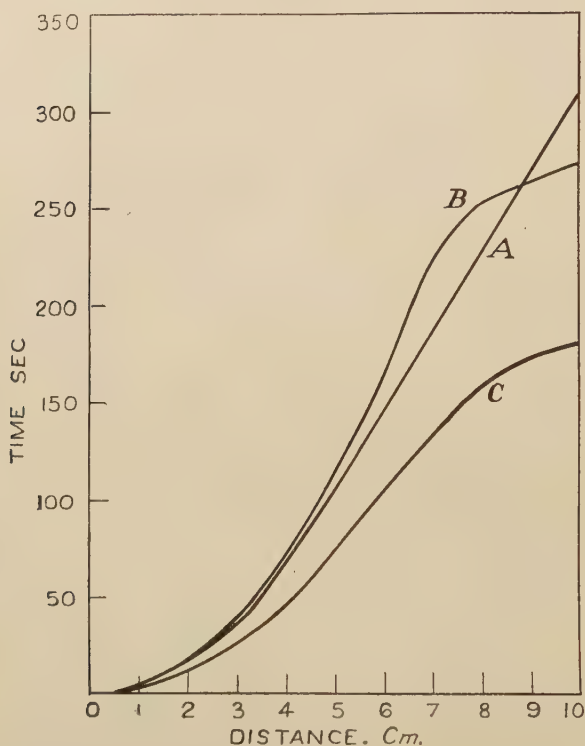


FIG. 40.

obtained a second approximation it would have been still nearer to the result obtained by the present author.

Again the importance of the effect of latent heat is apparent in the different characters of the two curves *A* and *C* of Fig. 40. It appears that in this case also the velocity of the critical plane is practically constant as it approaches the centre of the slab.

DISCUSSION.

The Report was discussed at the Additional Meeting held at Glasgow on May 9, 1929.

Mr. T. M. SERVICE (Glasgow) said the thermal method adopted by Professor Andrew and Dr. Binnie had not been used previously in determining the solidus, and the authors were to be congratulated on their perseverance in dealing with and overcoming the furnace difficulties experienced during the course of the work. The results obtained by that means of investigation agreed well with those obtained by other methods. One interesting point brought out in the investigation was that in carbon and nickel steel, provided the manganese was under 0.5 per cent. in the first and 0.45 per cent. in the second, the liquidus and solidus curves agreed well with the iron-carbon diagram. In everyday works experience one found that in straight carbon steels definite mechanical results could be obtained by keeping the manganese content constant at about 0.5 per cent. and varying the carbon, or by keeping the carbon content constant and increasing the manganese, the greater effect of the latter being obtained when 0.7 per cent. was exceeded. In the case of nickel or nickel-chrome steel the manganese content of 0.45 per cent. agreed well with everyday experience, as it was found that with a manganese content of over 0.5 per cent. the difficulties encountered in treating masses of those qualities were increased through greater hardness, increased liability to clinking, or formation of hair-line cracks, &c. Whether the solidification range had any bearing on the alteration of the properties found in a steel with the higher manganese content, further investigation might prove or disprove. The authors had extended the point *B* from 0.36 to 0.71 per cent. of carbon—that was the line *PQ* in the iron-carbon diagram (Fig. 9) showing the beginning of the deposition of δ mixed crystals now ended at 0.71 per cent. of carbon.

According to the authors' theory relating to the peritectic change :

- (1) A steel ingot, on complete solidification and still at a high temperature, was far from homogeneous, and
- (2) Diffusion did not occur on a falling temperature (see p. 340).

The experiment described on p. 339 and the result of the examination given on p. 340, illustrated by Figs. 10 to 15 (Plates XXXVI. to XXXVIII.), showed that in order to get complete carbon diffusion the material must be heated to a point short of incipient melting—that was, area 2 in Fig. 8. The theory of the peritectic transformation and the above-mentioned experiment agreed well with everyday experience; it was well known that steel ingots were very heterogeneous in the cast condition, and that little diffusion of carbon

occurred during cooling. On reheating, the amount of diffusion taking place depended on the speed of heating and on the final temperature to which the material was heated—that was, uniform heating—and the higher the temperature the greater the diffusion. An illustration of that point was the case of rolled ship or boiler plates. When cast they were lifted as soon as the ingot was set—in some cases the centre might even be plastic—transferred to heating furnaces and heated to temperatures varying between 1150° and 1300° C., cogged, and rolled to plates. Under the microscope sections taken from plates often showed a lamellar structure—that was, bands of ferrite and pearlite. It had been put forward as a reason for the existence of those ferrite bands that they might contain a high phosphorus content, or that silicates caused a migration of carbon, but Whiteley after investigating those suppositions came to the conclusion that some other reason must be found.

The idea put forward by the authors that steel immediately below its solidification point was not homogeneous, but consisted of large areas of iron almost free from carbon originally deposited in the δ form and areas higher in carbon, coupled with the fact that little diffusion took place on cooling, suggested an explanation. The non-homogeneous ingot was lifted hot, transferred immediately to a reheating furnace, and kept at a temperature somewhere in the neighbourhood of 1200° C.; little or no diffusion took place, due to the fact that the greatest amount of diffusion occurred on a rising temperature, and the amount of that was a function of time and temperature. The lamellar bands of ferrite and pearlite, he thought, were a result of the non-homogeneity of the original ingot.

The Report was further discussed at the Additional Meeting held at Sheffield on May 15, 1929.

Mr. E. H. SANITER (Vice-President) said that he had always maintained that manganese sulphide did not exist in steel until the steel was close to the solidifying point; he based that contention on the fact, so well established by the Committee on the Heterogeneity of Steel Ingots, that there was practically no corresponding segregation of manganese along with the sulphur. He must agree that up to date, as Professor Andrews and Dr. Binnie said, there was no definite conclusion on that rather important point. They were of opinion that manganese sulphide was not soluble in solid steel, but that hardly met the point that they went out to investigate, although it was useful information to have. Under certain circumstances, they found that iron sulphide was soluble in solid steel, but was liberated on reheating. He suggested that the authors should continue their investigations, and try to discover at exactly what temperature manganese sulphide could exist.

Dr. W. H. HATFIELD (Member of Council) said on behalf of the Committee that they were anxious to have comments on the Report. They were trying to build up that fundamental knowledge which was necessary before they could really attempt to draw a picture of the freezing of an ingot, and they hoped that the various sections of the Report would receive very serious consideration. For instance, it would be of value to them to know whether the thermal method was considered a satisfactory one for laying down once and for all the liquidus and solidus of commercial steels.

The CHAIRMAN (Professor C. H. Desch, F.R.S.) called attention to one of the more important conclusions in Section II. It would be seen that the authors laid very considerable stress on the peritectic change, which they said extended as far as 0.7 per cent. of carbon. That, in fact, was in accordance with the earlier determinations, although by a curious error all the text-books and later papers had set that limit at about 0.35 per cent., instead of 0.7 per cent., where it should be. The authors had concluded that the separation at that point accounted for a large part of the structure of an ingot—that, in fact, a great part of the ferrite which was observed afterwards in comparatively low carbon steels had not been formed by a secondary change from austenite, but had resulted from the original peritectic transformation. That was a very novel and controversial view. As regards Section V., by Mr. Lightfoot, previous work on the analysis of the solidification of steel ingots had been vitiated by the very large assumptions which had been made. Several papers, such as that of Feild referred to, had been very frequently quoted, but the reasoning contained in them was completely false. The much more serious paper by Saitô led to results which were not consistent with what was observed, and Mr. Lightfoot had carried the mathematical study of that process much further than Saitô had done.

Mr. H. SUTTON (Farnborough, Hants.) asked Mr. Lightfoot whether he considered that the supercooling of steel would seriously affect the conditions obtaining in an ingot, and also whether the fact that the freezing might be rapidly followed by the peritectic thermal change in carbon steels containing up to 0.7 per cent. of carbon would also be likely to have a very serious effect. It might be, of course, that the amount of heat associated with the peritectic change would be very small compared with that of the latent heat.

Mr. F. L. TINGLE (Sheffield), referring to Professor Andrew's point concerning the slower diffusion of carbon that occurred in steel ingots, desired to ask him (Professor Andrew) to explain the distinct line of demarcation between areas 1A and 1B in Fig. 10. Had that come about as a result of the steel being overheated, or was it due to the segregation of an element other than carbon, such, for instance, as silicon?

If not, then the appearance of that micrograph suggested that rapid diffusion had taken place at some stage of the heat treatment, rather than slow diffusion.

CORRESPONDENCE.

Professor C. BENEDICKS (Hon. Vice-President) (Stockholm) wrote : The result of the thermal analysis reported in Section II. is very gratifying, and proves the pure iron-carbon diagram to be valid for the commercial steels. It is desirable, however, that details should be added regarding the character of the melting and freezing curves—whether they are differential curves (no comparison body is mentioned) or inverse rate curves. A temperature scale would be highly desirable ; at present it is impossible to check the temperature readings, as, for instance, in Fig. 4, *W*, where the same temperature, 1472°C. , is indicated at two rather widely differing points.

The possibility of checking the temperature readings is not a matter of indifference, as the diagram given differs considerably from that obtained by Ruer and Klesper¹ ; in the latter the point *C* was found to be situated at 0.4 per cent. of carbon, while the present authors now indicate the astonishingly high value of 0.7 per cent. As a matter of fact, the former value, or at most 0.5 per cent., seems to square the present observations better than 0.7 per cent.

The authors assert that the usual way of interpreting the peritectic transformation is misleading, as the change solid *A* + liquid *C* = solid *B*, which has a tendency to diminish the number of phases existing at the peritectic temperature, is said to be not in accordance with the phase law (p. 341). This statement—the present writer is sorry to say—is based on a misunderstanding. On abstracting heat from the system *Y*, the temperature decreases ; two phases exist, one corresponding to *PA* and one to *PC* (Fig. 9). This goes on until the peritectic temperature, characterised by the fact that the phase *A* begins to react with the liquid phase *C*, forming a new, third phase *B*, is reached. The heat generated in this reaction causes a cooling arrest at the peritectic temperature *with all three phases present* until the phase *A* finally disappears ; only then will the fall of the temperature continue.

It is of course quite permissible to consider the peritectic transformation as being “a transference from one system to another” (p. 343), but there is no justification for saying that “the sharpness of the point” shows that the peritectic point is *not* due to the interaction of two phases ; we have only to consider the extreme sharpness of a eutectic point observed on heating, where two solid phases interact at a strictly constant temperature.

As for the phase rule, it may be pointed out that the theory of

¹ See R. Ruer and F. Goerens, *Ferrum*, 1917, vol. xiv. p. 161 ; or P. Goerens, “Einführung in die Metallographie” (Halle-a.-S., 1922), p. 228, Fig. 201.

heterogeneous equilibrium necessitates a definite angle between the liquidus PC (Fig. 9), corresponding to the solidus PA , and the adjacent liquidus which corresponds to solidus BQ . Such an angle is actually introduced into Fig. 9—though not in Figs. 5 to 7—but the equilibrium theory demands the angle to be such that the extension of the second liquidus falls inside the angle PCA , not beyond.

The micrographs, Figs. 10 to 15, are extremely beautiful; unfortunately it seems impossible to decide from them whether the structures are influenced in a noticeable way by the peritectic transformation. Apparently, the appearance of heterogeneity might be explained without considering this transformation.

Professor C. BENEDICKS (Hon. Vice-President) and Mr. H. LÖFQUIST (Stockholm) wrote concerning Section III.: The question regarding the solubility of sulphur in iron in the absence or presence of manganese is a very important point for the slag problem, and well deserves consideration. Previously it has been supposed that the solubility of sulphur in γ -iron is higher than in α -iron. The results reported by Friedrich,¹ however, are rather doubtful; hence it is very valuable that the present determinations by means of a series of cooling curves seem to have well established this fact. Of course, it must be kept in mind that the solubility of sulphur depends considerably on the simultaneous presence of oxygen.

Regarding the solubility of the MnS phase—known to contain up to 50 per cent. of FeS —in molten iron, it is of interest to find, from the data given in the Report, that an alloy containing 1.3 per cent. of Mn and 0.26 per cent. of S will, on solidifying, form primary iron dendrites (see Figs. 30 to 32), surrounded by regions which may be regarded as representing the eutectic mixture $Fe + MnS$. This is of some interest regarding the situation of the corresponding eutectic curve. This part of the $Fe-Mn-S$ system has been drawn by the present writers.² The observation shows that the curve EF must actually be situated so that the point falls below it (on the liquidus surface of iron).

It may be noticed that the critical point found to occur at $750^\circ C$. in the binary system $Fe-Mn$ (Fig. 26)—included as important to know in the present case—differs widely from earlier observations. For a content of 1.5 per cent. of Mn , Esser and Oberhoffer³ found Ar_3 to occur at $810^\circ C$., or 60° higher. The critical temperature observed, $817^\circ C$. (Figs. 24 and 25), must represent a definite point on the $\gamma-\alpha$ transformation surface of the iron phase in the ternary system $Fe-Mn-S$. This surface could be determined if some additional similar determinations were available.

¹ K. Friedrich, *Metallurgie*, 1910, vol. vii. p. 257.

² *International Congress for Testing Materials* (Amsterdam, 1927), p. 265, Fig. 3.

³ *Werkstoffbericht des Vereines deutscher Eisenhüttenleute*, No. 69, 1925.

Professor C. BENEDICKS (Hon. Vice-President) (Stockholm) wrote concerning Section IV.: The determinations of the specific gravity of molten metals executed in Stockholm have been entirely confined to the method used there (communicating U-tubes), as this was considered far more reliable than any other method conceivable. Hence, it is very interesting to learn something regarding the results obtainable by means of the Archimedean principle. The main difficulty of this method—apart from that of knowing exactly the volume of the sinker—is the unknown capillary action at the surface of the molten metal.

In Table A are reproduced the values given by the present authors and the corresponding values obtained at the Stockholm laboratory in the latest and most accurate determinations by N. Ericsson and G. Ericson. The values for low carbon were actually measured, the others interpolated.

TABLE A.—*Comparison of Sheffield and Stockholm Density Determinations.*

Carbon Content. %	Temperature. ° C.	Density.		
		Sheffield Determinations.	Stockholm Determinations.	Difference.
0.03	1530	(6.79)	7.18	...
	1545	7.05	7.17	...
	1560	6.97	7.16	...
0.04	1550	6.95	7.17	...
	1545	6.97	...	...
	1550	7.06	...	...
Mean 0.04	1545	7.00	7.17	+ 0.17
3.38	1300	7.26	6.93	— 0.33
3.54	1340	7.23	6.83	— 0.40
3.65	1320	7.31	6.88	— 0.43
3.65	1310	7.28	6.89	— 0.39
3.12	1465	7.17	6.77	— 0.40
3.38	1405	7.23	6.82	— 0.41
3.34	1345	7.32	6.88	— 0.44
3.14	1350	7.23	6.90	— 0.35
Mean 3.40	1355	7.25	6.86	— 0.39

As will be seen from the lower part of the table, the difference between the two sets of determinations is a remarkably constant one. This indicates that, apart from sources of error due to the methods, each set may be rather satisfactory. The mean difference, — 0.39, however, is an astonishingly large one.

It may be supposed that there is no considerable error due to the volume of the sinker. On the other hand, on account of the large diameter of the stem of the sinker (8 mm.), it is evident that the error due to capillary action may be very considerable. The apparatus is calibrated by weighing in mercury at room temperature t , so that correct results are to be expected only in the case of a metal possessing at a temperature T a capillary constant, α_T , equal to that of mercury ($\alpha_{Hg,t}$). If α_T of the metal to be determined is larger than $\alpha_{Hg,t}$, the (apparent) density obtained must be too high; on the contrary, if α_T is less than $\alpha_{Hg,t}$, the density obtained must be too low. From this the interesting conclusion may be drawn, that *the capillary constant of pig iron at about 1350° C. is considerably higher than that of mercury at room temperature.* Further, on account of the difference in the upper part of the table (+ 0.17) being of different sign, we may conclude that *the capillary constant of iron at about 1550° C. is actually lower than that of mercury at room temperature.* These conclusions, of course, are valid only on the probable supposition that the other possible sources of error in both methods used are small in comparison with that of the capillary action.

Mr. G. F. COMSTOCK (New York) wrote: The careful work of Professor Andrew and Dr. Binnie on the difficult subject of the liquidus and solidus curves of commercial steels will surely be appreciated by metallurgists, and the writer would not wish to appear inappreciative of its value in offering the following criticisms of some details of possibly minor importance.

The authors' interpretation of their micrographs on Plates XXXVI. to XXXVIII. does not seem entirely justified by common experience with cast steel. Structures similar to all those shown are not at all rare in steel castings that have not been annealed, or that have been "annealed" ineffectively. The accompanying Fig. A (Plate XLa.), for instance, taken from the interior of an ordinary test-bar casting, shows a structure similar to the authors' Fig. 10. In this instance, the structure could not possibly be due to a temperature gradient, but must be explained rather on the basis of segregation or different crystallising tendencies of the separate austenite grains. Might not a similar explanation also fit the authors' Fig. 10? Their Fig. 11 would seem to show merely a sorbitic structure, due to comparatively rapid cooling through the critical range, rather than a migration of carbon.

The interpretations given for Figs. 12 and 15 are that the former shows incipient melting, while the latter shows complete melting. This is difficult to understand, since these structures appear to be of exactly the same type, Fig. 15 simply being somewhat coarser than Fig. 12. It is not clear just what the authors consider to be a sign of melting in these structures, unless it is the areas showing the very fine mixture of pearlite and ferrite. Such areas have often been seen in the examination of cast steels in the writer's laboratory, where they are

called "feathery structure," as distinct from "angular." How can this structure be considered as an indication of melting, when it may be found as any fraction of the total structure, from zero to nearly 100 per cent., in steel castings, all of which cooled from the completely molten to the completely solid state in the mould? The accompanying Figs. B and C, for instance, show in one case an angular structure with one spot "feathery," and in the other case a "feathery" structure with a little angular, both in steel as cast. One steel here could not have been any more molten than the other, either during or after casting.

It is regretted that this criticism cannot be of a more constructive nature, but the fact is that the writer is unable to offer a satisfactory explanation for this variation in structure of cast steel, and hopes that the authors may throw more light on the subject in their reply. The "feathery" structure has been found more often in titanium-treated than in untreated cast steel, and also is more common in thin castings that cool rapidly. An explanation based on rate of cooling would seem more satisfactory than the authors' apparent connection of this structure with melting.

In drawing conclusions as to diffusion from the authors' results with the small piece of steel illustrated by the micrographs that have just been discussed, it should be borne in mind that there was a marked temperature gradient in the sample, and also that the alundum casing may have had an effect on the carbon content at points raised to certain temperatures. It does not seem to follow necessarily that in the interior of a larger mass of steel, heated uniformly, diffusion would be as slow, or as irregular in its results, as was found in the authors' experiment.

Another point that was of special interest to the writer was the difference in the arrangement of the manganese sulphide inclusions shown on Figs. 30 and 32. The difference here is explained on the basis of cooling speed, which seems entirely reasonable in this instance. It is a fact, however, that steel castings treated with aluminium almost invariably have the network sulphide arrangement illustrated by Fig. 32, while castings made without aluminium more often have the typical globular sulphides as illustrated by Fig. 30, though generally more evenly scattered. In foundry experience this effect is obtained irrespective of size of casting or rate of cooling. This has been described by the writer,¹ and the explanation tentatively offered was that aluminium may increase the solubility of the sulphides in the steel so that they are not precipitated until the steel becomes too viscous to permit them to agglomerate into larger spheres. Can the authors offer any further explanation of this peculiar effect of aluminium on sulphide inclusions in steel castings, in view of their work on sulphides now under discussion?

¹ *Iron Age*, 1924, vol. cxiv., Dec. 4, p. 1477.

Dr. M. S. FISHER (London) wrote that he thought that the difficulty encountered by Professor Andrew and Dr. Binnie in measuring temperatures above 1400° C. with the heating current on (Section II.) must have been due to the fact that the furnace winding was at a potential below earth-potential, the positive side of the supply current being earthed instead of the negative side. The authors found that no improvement was made by charging the grid to various potentials. Did they try the effect of a negative potential of the order of 250 v.?

The authors' interpretation of the peritectic transformation was interesting in that it tended to simplify a difficult problem. One point in their argument, however, was open to question. On p. 343, par. 3, the authors said: "Consider an alloy of composition Y . Freezing will begin at F_2 , and at a lower temperature, f , there will be present relatively af of liquid and fc of solid (δ -iron with some carbon in solution). Below the peritectic temperature, at f_1 , when equilibrium has been established there would be relatively f_1c_1 of the B constituent, and ef_1 of the liquid remaining. It is thus seen that as the peritectic change is passed through the solidus changes from PA to BQ and an amount of solid approximately equal to $(Af_2 - Bf_2)$ will separate and freeze spontaneously." The authors apparently meant that when the peritectic reaction began, the δ solid solution previously deposited was practically isolated from the system; the liquid, in effect, started to freeze over again, depositing austenite of composition B . An effect approximating to that outlined in the preceding sentence was commonly produced at the peritectic transformation, because of the slowness of solid diffusion. But partial isolation of the δ solution from the system would not result in spontaneous freezing of an amount of solid approximating to AB . If the δ solution were completely isolated from the system, the active part of the alloy would consist of liquid of composition C . The amount of solid that would form under those conditions, when the temperature passed through the peritectic temperature and fell to that of line $a_1f_1c_1$, could be found by dropping a perpendicular from point C to line $a_1f_1c_1$, meeting that line at, say, c_2 . The amount of solid forming in the interval specified would then be represented by segment c_2c_1 of line ec_1 , which would be very small if line $a_1f_1c_1$ were close to line ABC . Under those conditions, the evolution of heat caused by solidification at the peritectic temperature would be extremely small. The amount of solid that formed at the peritectic transformation depended on the extent to which the δ solid solution reacted with the liquid. Only under ideal conditions, when the reaction went to completion, would the amount of solid formed at that temperature be represented by the difference between $\frac{f_2C}{BC}$ and $\frac{f_2C}{AC}$.

Dr. J. M. ROBERTSON (London) wrote that many new conceptions had been proposed, particularly in Section II., and it would be some 1929—i.

time before the implications of those ideas would be embodied in our general view of the phenomena. In one part of the Report Professor Andrew and Dr. Binnie had applied some of those new ideas to the interpretation of microstructure, but he (Dr. Robertson) did not think that their explanation was the only one possible. The structure shown at the right-hand side of Fig. 10 was common enough, and the factors which caused its formation were fairly simple. They need not be described in detail; it was sufficient to say that the formation of that structure was influenced by the size of the austenite grains, the carbon content, and the rate of cooling. It was more easily produced in large grains than in small grains, and it was associated with overheating, because overheating produced large grains of austenite. The structure in question was not associated with any particular temperature above which the steel must be heated to produce it. The difference between areas 1A and 1B in Fig. 10 was not due to the difference in the temperature at which they were heated. They were simply two adjacent large grains which were probably very similar in three dimensions, but appeared different on a plane section which cut the grains at different angles. It was obvious that the ferrite needles in area 1B would not necessarily have the same elongated form if a section were cut at right angles to the surface shown in Fig. 10, for no elongated shapes looked the same in all directions. Those needles might be prisms or plates. If they were rough prismatic shapes with one long axis, their appearance on a surface at right angles to that of area 1B would resemble the structure shown in area 1A. The same argument applied to the structures in Figs. 13, 14, and 15. All those structures might be explained by assuming that the whole specimen consisted of approximately similar grains, each of which was composed of a framework of ferrite plates or prisms, parallel to the crystallographic planes in the austenite. The spaces in that framework would of course be filled with pearlite, and the respective amounts of ferrite and pearlite on any plane section, and the distribution of those constituents with respect to each other, would depend on the angle at which the grain was cut. The structure shown in Fig. 12 was different from the remainder of the structures, because in that area the austenite crystals were relatively small compared with the others.

Professor ANDREW and Dr. BINNIE, in a written reply to discussion on Sections II. and III., thanked Mr. Saniter for his useful comments. His suggestion that manganese sulphide did not exist in steel until the temperature approached the freezing point was a view held by many, and it was their intention to investigate that possibility as soon as possible.

With regard to the point raised by Mr. Tingle, the authors believed that the line of demarcation was due to the promotion of rapid diffusion by overheating. They did not contend that diffusion was slow under all conditions; it might occur rapidly under a rising or

at a steady temperature, but only to a small extent on a falling temperature.

They welcomed the remarks of Professor Benedicks. Their curves were all plotted as inverse-rate curves. Since three different thermocouples, which differed slightly from one another, were used in this investigation, and since millivolt-time readings were taken, to have plotted these on a definite temperature scale would have necessitated a considerable amount of work, so it was thought that if the actual temperatures of the critical changes (as taken from the figures) were given in each case that would suffice. That accounted for the non-correspondence of the temperature readings in the same figure. Their reason for giving the value of 0.71 per cent. for the carbon composition corresponding to the limit of the peritectic change was that that figure corresponded to the point at which freezing coincided with the temperature of the peritectic transformation, and, further, it coincided with the extrapolated values for the other purer steels. With regard to the peritectic reaction, it was noticed in every freezing-point determination made that the heat evolution immediately on solidification was very large, indicating that the greater part of the alloy became solid at the commencement of freezing. That being the case, it was extremely difficult to believe that interaction between a (relatively) large mass of solid and a smaller amount of liquid could so completely take place at a constant temperature as to give rise to a large evolution of heat over a very small time interval. The authors believed that that was due, as they had stated, to the sudden solidification of solid *B* (Fig. 9), and, chiefly, to the transformation of the previously deposited δ iron into the γ state.

In Figs. 5 to 7 the angle spoken of was absent on account of the fact that sufficient points at the higher carbon end of the diagram were not obtained. The authors of course fully realised that Professor Benedicks' contention was quite correct.

They were extremely interested in his remarks on the iron-manganese-sulphur system. They did not wish to lay too much stress on that work, which was only of a purely qualitative nature.

In reply to Mr. Comstock, they desired to point out the method by which the structures referred to by him were obtained. A bar of steel, 10 cm. in length, was placed in the furnace so that part of it lay within the hottest zone of the furnace, and part within a relatively cool zone. The furnace was heated for 1 hr. with a current which was known to be sufficient to completely melt that part of the bar lying within the centre zone. That that part had actually been melted was further proved by the change in its configuration noted on its withdrawal from the furnace. That a temperature gradient had existed was thus beyond doubt. It was an actual fact, therefore, that Fig. 15 (Plate XXXVIII.) corresponded to a portion which had been completely melted. As had already been pointed out, the authors considered their experiments on manganese-iron-sulphide alloys to be too

qualitative to allow them to form any definite conclusions, and they regretted that they were unable to answer Mr. Comstock's question regarding the effect of aluminium. They could only suggest that aluminium might affect the solubility of sulphides in liquid steel and, therefore, the form taken up by the solid sulphide on deposition.

Dr. Fisher's suggestion that the thermocouple trouble was due to a difference in potential within the furnace did not seem to explain why the trouble only arose at temperatures above 1400° C., and, further, why on insulating the couple in the usual manner that peculiarity did not disappear.

Dr. Fisher raised one or two interesting points with reference to the peritectic transformation. The authors did not wish to give the impression that a temperature-composition diagram could be used to calculate actual quantities of liquid and solid coexisting at the same temperature; ratios only could be dealt with. Dr. Fisher suggested that the heat evolution at the peritectic temperature due to deposition of solid *B* could only be small, on account of the relatively small amount of solid actually deposited. With that they agreed, but would remind Dr. Fisher that he had neglected to take into account the change of the previously deposited δ -iron into its γ form, which accounted for the greatest proportion of the heat evolution, and would, by keeping the temperature constant for a small time interval, allow of a certain amount of the constituent *B* to be deposited.

Dr. Robertson's comments were interesting. His contention that the different structures obtained in the bar (Fig. 8) were not due to the rate of cooling, but depended upon the angle at which the grains were cut, was difficult to agree with. In Fig. 8 definite boundaries were drawn, and it was found that in each area the structure was approximately the same over the whole cross-section. Had the difference been purely one of orientation, it was difficult to understand how that condition could pertain. The authors did not for one moment wish to give the impression that similar structures could not be obtained by other methods.

They were exceedingly grateful to Mr. Service for pointing out a close agreement between their theories and suggestions and actual practice. Such remarks as Mr. Service had made not only greatly assisted to substantiate the many statements made, but also showed that an investigation such as the present one had a distinct practical bearing.

Professor DESCH and Mr. SMITH wrote: The only criticisms of Section IV. are those from Professor Benedicks. The high value for the density of the molten high-carbon iron at 1350° C. is certainly surprising, and it may be that there is some constant source of error which has not yet been discovered. The object of the communication was to show that a method had been devised which gave promise of yielding accurate results. It cannot be admitted, however, that the

error is of the nature suggested by Professor Benedicks. The capillary correction for the suspending rods used amounts only to 1 per cent. of the displacement. An examination of the sinker during the experiments showed that the stem was not wetted. A series of tests, using suspending rods of different diameters, for which therefore the capillary correction would be different, gave identical results. It is, moreover, highly improbable that there should be so great a range in the capillary constant of molten iron within the range of temperature examined. Further experiments are being made to determine the exact coefficient of expansion of the various sinkers used.

Since the discussion on the paper, a further research on the density of molten white iron has been published by Zimmermann and Esser.¹ These authors used a cylindrical porcelain crucible containing the metal, and measured the rise of the liquid level at different temperatures by means of wires making an electrical contact, the displacement of these wires being measured optically. The experiments for iron with 3.5 to 3.9 per cent. of carbon gave excellent curves, indicating a density of the iron immediately above the melting point of 7.09. Extrapolation of their curves to 1350° C. would give a value of 6.93. In the light of the experience which has been gained, it is believed that the apparatus is capable of further improvement, whilst the method should provide a useful check on the determinations of Zimmermann and Esser, which are made in an entirely different manner.

Mr. LIGHTFOOT replied to Mr. Sutton that it was impossible to predict the effect of supercooling in the absence of precise experimental data, and without further analysis. The effect would depend on the amount of supercooling which occurred, but if that were only slight, it was likely that the conditions would not be seriously affected.

The effect of the peritectic change would depend on the relative amounts of heat involved. The general result would be a further slowing down of freezing. If a definite evolution of heat at a fixed temperature were assumed, it was possible, in the simpler cases I. and II., to calculate the effect accurately; but considering the rough assumptions made, it would scarcely be justifiable to regard as strictly accurate any results obtained by taking into account such small effects as the peritectic thermal change was likely to be.

¹ *Archiv für das Eisenhüttenwesen*, 1929, vol. ii. p. 867.

THE MICROSTRUCTURE OF RAPIDLY COOLED STEEL.*

By J. M. ROBERTSON, B.Sc., PH.D., A.R.T.C. (LONDON).

INTRODUCTION.

IN the first explanation of the occurrence of sorbite, troostite, and martensite, it was supposed that these constituents corresponded with a series of intermediate states through which the steel passed during the normal decomposition of austenite. This view of the occurrence of these constituents is described in most of the standard text-books. According to it, rapid cooling is simply a means of causing the temperature to fall more rapidly than the transformation can proceed, and the structure and constitution of steel at ordinary temperature depends on the difference between the time taken to cool through the critical range and the time required for the complete austenite-pearlite transition to take place.

Assuming that rapid cooling is a means of interrupting the austenite-pearlite change at some intermediate stage, it was natural to expect that the interrupted transformation would again proceed if a rapidly cooled steel were reheated. This inference from the theory of the effect of the rate of cooling formed the basis of the theory of tempering. Thus it was accepted that when a steel had been cooled to retain one of the intermediate states—say, martensite—it could be made to change to other states by reheating.

The prevailing theory of heat treatment during the period under discussion may be said to have consisted of five essential elements as follows:

(1) The normal change from austenite to pearlite (with ferrite or cementite) is a compound change, during which the steel passes through a succession of states.

* Received January 25, 1929.

(2) By suitably varying the rate of cooling, the steel may be retained at the ordinary temperature in any of these intermediate states, and each of these states corresponds to a definite micro-constituent, to which the names martensite, troostite, and sorbite have been given.

(3) The effect of the rate of cooling in retaining these intermediate constituents is due to the fact that the complete change from austenite to pearlite requires a certain time to proceed to completion ; if the time taken to cool through the critical range is less than that required for the complete transition, one or other of the intermediate states is retained.

(4) As the intermediate states are stages in a continuous change which is interrupted by rapid cooling, the change thus interrupted will again proceed if the rapidly cooled steel is reheated.

(5) Cooling at different rates, or rapid cooling followed by reheating to different temperatures, are alternative means of achieving the same object, which is to interrupt the austenite-pearlite change at the appropriate stage. This similarity between the results obtained by varying the rate of cooling and by varying the tempering temperature is implicit in the nomenclature.

The above explanation of the relations of martensite, troostite, and sorbite to each other and to the normal iron-carbon diagram was at one time widely accepted, but it has since been demonstrated by means of cooling, magnetic, and dilatation curves of carbon and alloy steels that a variation in the rate of cooling alters the temperature at which the change begins. Consequently, the effect of the rate of cooling is no longer attributed to the restriction of the time taken to cool through the critical range, but is now attributed to a lowering of the temperature at which the transformation begins.

The idea that quenching lowers the change point to a considerable extent was first proposed by Le Chatelier in 1897.⁽¹⁾ This view did not receive much attention at the time, and as experiments subsequently performed did not confirm the existence of this low change point, the matter remained in abeyance until conclusive evidence of a low change point in alloy steels inspired renewed investigation of the changes in carbon steel. In 1911 Grenet⁽²⁾ reopened the question, but again no serious attention was paid to this idea. It was not until 1917, in fact, that it began

to be generally realised that the effect produced by rapid cooling was due to a lowering of the change point. In that year Portevin⁽³⁾ published a summary of the work on alloy steels and showed the connection between the initial temperature, the rate of cooling, and the temperature of the change point in those steels. In a subsequent paper Portevin and Garvin⁽⁴⁾ showed that in carbon steels the transformation took place at a low temperature during quenching. The results of that work were confirmed by Chevenard⁽⁵⁾ and Dejean,⁽⁶⁾ and subsequently by Honda⁽⁷⁾ and other Japanese workers.

As a result of the above investigations, the following connection between the rate of cooling and the temperature of the transition has been established:—As the rate of cooling is progressively increased, the temperature at which the transformation begins is gradually lowered. When a certain rate of cooling is attained, however, there is a sudden discontinuous lowering of the change to the neighbourhood of 300°C . The rate of cooling required to produce this sudden lowering of the change is known as the “critical rate of cooling.” Rates of cooling considerably less than this critical rate produce slight lowering of the transformation temperature; when the rate of cooling approaches the critical rate the transformation takes place partly at a high temperature and partly at a low temperature, and when the rate of cooling equals or exceeds the critical rate, the transformation takes place entirely at a low temperature. The normal transition from austenite to pearlite during cooling is known as the Ar_1 , and, on the suggestion of Portevin, the change that takes place when the Ar_1 is slightly lowered is now called Ar' , and the low-temperature change Ar'' .

It is evident that the above modification of the third paragraph in the summary of the original theory does not necessarily imply any alteration of the remaining paragraphs, and many metallurgists still accept the view that martensite, troostite, and sorbite are intermediate stages in the change from austenite to pearlite, although they now regard the rate of cooling as affecting this change by lowering the temperature at which it begins, thereby limiting the extent to which it proceeds, and thus interrupting the transformation to retain at ordinary temperature one or other of the intermediate states. Honda, Sauveur, Lucas, and a

number of others accept this view, but the majority of steel metallurgists consider that the response of steel to heat treatment cannot be suitably accounted for by supposing that rapid cooling is a means of interrupting the austenite-pearlite transition at various intermediate stages. A new conception of the relation between the so-called transition constituents and the normal changes in steel has therefore been introduced.

According to this new conception of the effect of the rate of cooling, martensite, troostite, sorbite, or pearlite may be produced directly from austenite, and the temperature at which the austenite decomposes determines which constituent is formed. The various micro-constituents are not consecutive stages in a continuous change, but alternative products of the decomposition of austenite. As the Ar' point is progressively lowered by increasing the rate of cooling, the austenite transforms directly to sorbite or troostite instead of to pearlite, and when the critical rate of cooling is exceeded the austenite transforms at Ar'' and produces martensite. Whereas in the terminology of the original theory it is said that rapid cooling retains martensite, in the terminology of the new theory it is said that rapid cooling produces martensite.

This new conception of the response of steel to variations in the rate of cooling is largely due to the French metallurgists, notably Portevin, Chevenard, Dejean, and Le Chatelier, and it is now accepted by many metallurgists, although this is by no means general.

It may now be said that all metallurgists agree on the existence of the Ar' and Ar'' points, and practically all accept the view that sorbite and troostite are formed at Ar' , whereas martensite is formed at Ar'' . The main division of opinion is between those who think that the Ar'' change is the complete transition $\text{austenite} \rightleftharpoons \text{martensite} \rightleftharpoons \text{troostite} \rightleftharpoons \text{sorbite} \rightleftharpoons \text{pearlite}$ interrupted at the martensite stage, and those who think that the Ar' is a direct change from austenite to pearlite, sorbite, or troostite, and the Ar'' a direct change to martensite. Those who accept the former view have to find an explanation for the discontinuous lowering of the change from Ar' to Ar'' , for it is natural to expect that if one change only were involved, it would be progressively depressed by an increase in the rate of cooling. Honda and Kikuta⁽⁸⁾ have evolved an explanation of this discontinuity based

on the "tendency" of the change to take place and the "resistance" it has to overcome. Those who consider that the Ar'' is a different change from the Ar' have to explain this difference and describe the nature of the Ar'' . Various explanations of the Ar'' have been proposed. Portevin and Chevenard⁽⁹⁾ consider that Ar'' marks a position of labile equilibrium between a solid solution of carbon in γ -iron and a solid solution of carbon in α -iron. Hanemann and Schrader⁽¹⁰⁾ have proposed an explanation that assumes the appearance, under the requisite conditions, of a new modification of iron. Other explanations of the difference between Ar' and Ar'' have been proposed by Scott,⁽¹¹⁾ Dejean,⁽¹²⁾ and Hallimond.⁽¹³⁾

Superficially it might appear that the difference between the two views of the response of steel to variations in the rate of cooling is largely one of terminology, and that, so far as the tangible and practical results of heat treatment are concerned, it is immaterial which is true and which false. This, however, is not the case, for the implications of the two theories and the deductions that may be drawn from them differ so widely that they must be considered to represent fundamentally opposed conceptions of the response of steel to heat treatment. The object of the present paper is to describe certain experiments on the effect of cooling steel at different rates, and to show how these results are related to what has been called the new conception.

INVESTIGATION OF THE MICROSTRUCTURE OBTAINED BY DIFFERENT METHODS OF COOLING.

The modification of the constitution, structure, and general physical and mechanical properties of steel by heat treatment depends on the fact that the changes which normally occur during cooling are affected by time. Theories of heat treatment are really theories of the effect of the time factor on the changes that are represented in terms of temperature and composition by the iron-carbon diagram. The time factor is varied by varying the rate of abstraction of heat, and it may therefore be said that the study of the phenomena associated with the heat treatment of steel is a study of the effect of the rate of abstraction of heat.

Two aspects of the rate of abstraction of heat must be considered. In the first place, the rate of abstraction of heat controls the temperature at which the change begins, and once the change is in progress, it controls the conditions under which it takes place. The temperature at which the change begins and the conditions under which it proceeds determine the product of the change. Investigation of the phenomena associated with heat treatment, therefore, becomes investigation of the effect of causing austenite to transform at different temperatures and under different conditions with respect to the rate of abstraction of heat. This is the fundamental fact underlying all methods of varying the rate of abstraction of heat, and no particular significance can be attached to cooling in media held at ordinary temperatures, for the results obtained by cooling in media held at higher or lower temperatures are equally important.

In the wire industry it is common practice to heat-treat the small rods used for wire-making by cooling in molten lead. According to the earlier views on heat treatment, this method of cooling should produce results similar to those obtained by quenching followed by tempering. Actually, however, the structures produced by cooling in molten lead have no relation to those produced by water-quenching and tempering. As long as the temperature of the lead is lower than that at which the austenite transforms, cooling in molten lead resembles cooling in any other medium—that is, as the temperature of the lead is varied, the rate of cooling before the change and the rate of abstraction of heat during the change are varied together. If, however, the austenite does not transform before the steel attains the temperature of the lead in which it is immersed, it will inevitably transform while the steel is at the same temperature as the lead, and the rate of abstraction of heat during the change may then be varied independently of the rate of cooling before the change. It is this aspect of lead cooling that is of special importance.

The present investigation was undertaken to determine the sequence of microstructures produced by cooling in molten metal at progressively varying temperatures. Some hundreds of specimens have been heat-treated and examined; the effect of varying the composition and diameter of the specimens, and

of varying the temperature of the cooling medium, has been studied.

The sequence of structures produced by varying the temperature of the cooling medium is of fundamental importance; on the other hand, the actual structure produced in a rod of a particular size and composition by cooling in metal at a certain temperature is influenced by so many variables that it would be practically impossible to prescribe the exact conditions necessary to obtain a specific structure. The number of factors that influence the product of a given heat treatment is greater in the case of cooling in molten metal than in the commoner heat treatment operations, for, in addition to the usual variables—initial temperature, size, composition, and cooling medium—the time of immersion and rate of movement while in the medium are introduced. The rate, or amount of movement while in the medium, is not without influence during water and oil quenching, but owing to the comparatively sluggish convection in molten lead or other metal the importance of movement is greatly magnified.

In the present paper attention is confined to the fundamental aspects of cooling at intermediate rates—that is, it is confined to a consideration of the sequence of structures obtained by varying the temperature of the medium. The description of these structures would be needlessly confused by attempting to consider too many variables at the same time; therefore the description is restricted to steel rod of one composition, namely, 0.75 per cent. of carbon, and one diameter, namely, 0.11 in. The structures described in the following pages may be obtained in any steel, subject to certain limitations with respect to the size of the specimen. These structures are part of the phenomenon of the response of steel to heat treatment, and consequently they are considered in relation to the theory of heat treatment as a whole.

To facilitate the description of the structures obtained with progressive variation in the rate of cooling, they have been divided into seven groups, each illustrated by a number of micrographs. This division into groups is more or less arbitrary, for, except for one pronounced break in the sequence, the structural transition is absolutely gradual. To avoid confusing the text, the

micrographs are described in terms of the structures shown. The heat treatments given to the specimens, and the micrographs taken from each, are shown in Table I. All specimens were etched with 1 per cent. nitric acid in alcohol. The micrographs at 430 diameters were taken with a 3-mm. objective, and those at 820 diameters with a 2-mm. oil-immersion objective. The same eyepiece and camera extension were used with both objectives.

TABLE I.—*Heat Treatment of Specimens.*

Specimen No.	Treatment.	Figure Nos.
<i>A</i>	Cooled in furnace	1
<i>B</i>	Rapidly cooled in furnace	2
<i>C</i>	" " "	3, 4
<i>D</i>	Cooled in molten metal at 480° C.	5, 6
<i>E</i>	" " " " 400° C.	7
<i>F</i>	" " " " 420° C.	8 to 12
<i>G</i>	" " " " 410° C.	20, 22
<i>H</i>	" " " " 400° C.	13, 14, 18, 19, 21
<i>I</i>	" " " " 400° C.	15 to 17
<i>J</i>	" " " " 390° C.	23 to 30
<i>K</i>	" " " " 380° C.	31 to 34
<i>L</i>	" " " " 380° C.	35 to 39
<i>N</i>	Cooled in molten metal. Gradient	40 to 42

Specimens *C* and *E* to *N* were 0.1 in. in diam. and contained 0.75 per cent. of carbon.

Specimen *D* was 0.25 in. in diam. and of the same steel.

Specimens *A* and *B* were 0.1 in. in diam. and of the same steel, but were carburised for 4 hr. in coal-gas.

Group 1 Structures.

The structures of this group are illustrated by Figs. 1 and 2 (Plate XLI.). Fig. 1 shows the normal pearlite characteristic of slowly cooled steel. Each of the original austenite grains has transformed into one grain of pearlite, and in each of the latter the ferrite and cementite laminations have a uniform orientation—that is, the plates run in parallel lines right across the grains.

Fig. 2 shows a cementite envelope enclosing a grain in which the laminations in the pearlite run in a number of different directions. This type of structure does not as a rule occur in the same specimens as that illustrated in Fig. 1, and it is probably produced with slightly different rates of cooling.

When the rate of cooling is slightly increased the arrangement of plates illustrated by Figs. 1 and 2 does not persist. Instead, a number of different orientations develop in each of the original austenite grains. This effect may be observed in any steel containing more than 0.2 per cent. of carbon, but it is best observed in hyper-eutectoid steels, in which the original austenite grains are marked off by the pro-eutectoid cementite. Some of the steel used was therefore heated for 4 hr. in coal-gas, and was then cooled at various slow rates. It was observed that a slight increase in the rate of cooling caused the individual grains to break up into a number of pearlite grains.

Each increase in the rate of cooling appears to increase the number of different orientations in each original austenite grain. But within the range of slow cooling it is difficult to vary the rate accurately. The specimens used in this part of the work were heated in the middle of a tube furnace, then drawn towards one end and allowed to cool in the furnace. By this means the rate of cooling was varied slightly and the structures mentioned were obtained.

The alteration in the disposition of the pearlite laminations with reference to the original austenite grains does not at first appear to follow any definite law. Near the boundaries of the original grains the orientations appear to have developed from the grain boundary, but on the whole the laminations seem to be oriented at random. When a certain rate of cooling is reached, the subsidiary orientations of the laminations begin to be arranged in a particular way within the boundaries of the original austenite grains. As the rate of cooling is further increased, this vague arrangement of the subsidiary orientations becomes very definite, and gives rise to the structures of Group 2.

Group 2 Structures.

In the structures of this group the subsidiary orientations of the laminations radiate from a centre, and the plane surface seen under the microscope consists of a succession of fan-shaped units, as illustrated in Figs. 3 and 4. As the whole surface is composed of these fans, it is evident that the three-dimensional units are

such that the appearance of a section is independent of the direction in which it is cut. Therefore, the three-dimensional grains must resemble irregular spheres made up of a number of long crystals radiating from a centre.

The size of the fans depends on the size of the original austenite grains and on the rate of cooling. If the rate of cooling is just sufficient to give the fan or radial arrangement, each fan occupies one austenite grain. With quicker rates of cooling a number of fans may form in each austenite grain. The fans may therefore be made very large, as illustrated in Figs. 3 and 4, or so small as to be hardly recognisable.

Each fan consists of a number of radial segments, and each of these consists of alternate plates of ferrite and cementite. In each of the segments composing the fan, the ferrite-cementite laminations have an independent orientation; it is this feature that makes the fans recognisable under the microscope. When the fans are large the laminations can be resolved, and are shown in Figs. 5 and 6. When the rate of cooling is increased, the fans become smaller and the laminations closer; eventually the laminations become so fine that they cannot be resolved. As the gradual modification of the structure can be followed from ordinary pearlite to small irresolvable fans, it is rational to assume that the ultimate constitution of these fans remains the same, although the ferrite-pearlite laminations become indistinguishable.

When a specimen composed of the well-defined pearlite characteristic of slowly cooled steels is examined, the laminated structure may be recognised over the entire surface. The finer varieties of pearlite produced by slightly accelerated cooling cannot be completely resolved, and the laminated structure can only be seen in those areas in which there is a certain relation between the orientation of the plates and the surface examined. The remaining grains simply etch to different tints, varying from white to black. In specimens containing the fan structure, the laminations, even when resolvable, can only be seen in certain areas; but this does not indicate that those areas are the only ones in which the laminations exist. Lucas⁽¹⁴⁾ has examined the fan-shaped structures, called nodular troostite, that occur under certain conditions during water-quenching. His high-power micrographs reveal the laminations in certain parts of those

nodules, while the remainder is black and irresolvable. In accordance with his view of the relation of the micro-constituents, he considers that those micrographs illustrate the passage of troostite into pearlite. Actually, however, the nodules consist entirely of laminations of ferrite and cementite, but these laminations are only resolved when they have a certain orientation. It is the existence of these laminations and the variation in their orientation in the different radial segments that account for the orientation phenomenon observed by Lucas when a nodule of troostite was revolved about the optical axis of the microscope.

In the steel under consideration, the fan structure is obtained over a range of cooling rates; in fact, using the 0.11-in. diam. specimens the fan structure is obtained by cooling in air, and in molten metal at any temperature between 620° and 440° C. In general, the extent of the range of cooling rates within which the fan structure may be obtained depends on the composition of the steel. In steels containing less than 0.4 per cent. of carbon complete conversion to the fan structure is not easily obtained. As the carbon content increases, the number of cooling rates that produce the fan structure is also increased. In fact, in steels containing more than 0.6 per cent. of carbon the fan structure, and the structures resembling it, are formed over such a range of cooling rates that they are almost as easy to obtain as the normal ferrite-pearlite structures or the typical water-quenched structures. The commonness and the importance of a structure and the number of times it is observed depend on the range of cooling rates within which it may be obtained and the relation of these cooling rates to the methods of cooling in common use. The fan structure is almost invariably obtained when small specimens—under $\frac{1}{4}$ in. diam.—are cooled in air, when fairly large specimens of carbon steel are quenched in water, hot water or oil, and when specimens of a variety of sizes are cooled in molten lead. The fan structure and structures resembling it may therefore be called common. Micrographs of fans have been published by Schrader,⁽¹⁵⁾ and a considerable quantity of the high-carbon steel wire now made is manufactured from rod consisting of fans.

For reasons which will be described later, the fan structure may be obtained in association with any other structure formed

at a lower temperature. When this occurs the fans appear as isolated nodules in a ground-mass of the other structure. This gives rise to the structure known as nodular troostite.

As will be seen in Figs. 3 and 4, the individual fans etch differently. Dark-etching fans are commonest, particularly when the structure is fine, but in all examples of this structure light-etching fans occur. It follows from this that the fans that occur in association with other structures will usually etch readily and appear black under the microscope, but light-etching fans will sometimes occur. Fig. 7 (Plate XLII.) shows a white fan or white nodule. The specimen from which this micrograph was taken contained a large number of black fans, and the structure was typical of nodular troostite. The ground-mass consisted of structures of Group 6, which etch relatively quickly and appear dark by contrast with the white fans.

Group 3 Structures.

The structures of this group are entirely distinct from the fan structure, with which they may or may not be associated, according to whether the rate of cooling through the range in which the latter forms is rapid enough to interrupt or completely suppress its formation.

Figs. 8 to 10 (Plate XLII.) represent typical examples of this structure. It will be seen that the specimen is composed of an irregular arrangement of areas which etch to different tints. There is no systematic arrangement of these areas ; each seems to be independent of those surrounding it, and the light and dark areas do not combine to form a definite pattern.

At a higher magnification, as illustrated by Figs. 11 and 12, each unit area is seen to be finely laminated, and within each unit the laminations are perfectly straight and parallel. These laminations are most easily distinguishable in the dark-etching areas. In some of the white- and light-etching areas, however, the laminations may be seen. This structure is entirely distinct from the various modifications of pearlite described under Groups 1 and 2. It marks the beginning of a new type of structure, which undergoes a gradual modification as the temperature at which the austenite transforms is progressively lowered.

Group 4 Structures.

In the structures of this group, fine laminations are the ultimate components of the visible structure, and in this respect they resemble those of Group 3. In Group 4, however, the differently tinted areas combine to form a symmetrical pattern. Figs. 13 to 18 (Plate XLIII.) represent different areas in a specimen showing this type of structure.

When it is observed that a series of structures is repeated many times in a single specimen, it is necessary to decide whether the different structures composing the series are due to differences in the constitution and symmetry of the grains or simply to differences in the angle they make with the plane surface examined. It is unreasonable to suppose that pronounced differences in the constitution or symmetry of the various grains composing a small specimen could be produced. The grain is the unit by which the specimen is built up, and no theoretical reasons can be adduced for supposing that the individual grains could be differently affected by the imposed conditions. When a series of different structures is observed in a single specimen, it must therefore be assumed that the difference depends on the relation of the plane surface examined to the symmetry of the grains.

In the structures obtained in slowly cooled steels, there is no pronounced difference in the appearance of the grains when cut at different angles. Ferrite looks the same whatever section of the grain is examined, and pearlite is only slightly confusing. Whatever section of a pearlite grain is cut, the lamellar arrangement may be recognised, and difficulty arises only when attempts are made to decide whether the observed variation in the distance between the laminations is due to the angle at which the grains have been cut, or to an actual difference in the width of the plates. The various modifications of the pearlitic structure obtained when the rate of cooling is slightly increased are also simple, and although the individual fans in a specimen showing this structure etch differently, the symmetry in all cases is clear.

The structures included in Group 4 are examples of a structural type of considerable complexity, and the grains look quite different, according to the relation of the plane surface examined to the symmetry of the crystal. On examining such a specimen,

a series of different structures of similar symmetry is observed, and the problem is to construct the solid grain from the observation of random sections.

On the assumption that the separate grains composing the specimen are similar, Figs. 13 to 18 may be considered to represent different sections of the same grain at 430 diameters, and Figs. 19 to 22 (Plate XLIV.) may be regarded as showing the same thing at a higher magnification.

In the structures of Group 4, the dark- and light-etching areas which combine to form the symmetrical patterns are composed of minute laminations lying parallel in each uniformly tinted area, but varying in direction at different points in the same grain. It is these laminations that establish the connection between the structures of Groups 3 and 4.

Group 5 Structures.

Once the symmetrical pattern described in the previous section is obtained, further lowering of the temperature at which austenite decomposes produces modifications in the pattern without altering its basic symmetry. Figs. 23 to 30 (Plates XLIV. and XLV.) show the next phase in the structure. The constituent parts of the pattern are finer and sharper, and in some areas the structure is beginning to have an acicular appearance. The laminations composing the dark areas are hardly resolvable, but in some of the micrographs their presence is suggested.

As in Group 4, the micrographs illustrating the different two-dimensional structures of Group 5 must be regarded as different views of similar three-dimensional grains.

Group 6 Structures.

The structures of Group 6, illustrated by Figs. 31 to 39 (Plates XLVI. and XLVII.), represent another phase in the progressive modification of the symmetrical structure with the depression of the temperature of the transformation. In these micrographs the laminations composing the different areas cannot be resolved ;

as, however, the gradual disappearance of these laminations can be followed through a series of specimens showing the gradual change in the appearance of the symmetrical structure, it must be assumed that they are still the ultimate components of the structure.

The structures of this group are definitely acicular; notwithstanding this, the structures illustrated in Figs. 31 to 39 are clearly related to those of Group 5, and through them to those of Group 4.

Group 7 Structures.

The structures illustrated in Figs. 31 to 39 were obtained by cooling in molten tin at 380°C .; as the rate of cooling was further increased, by cooling in tin at lower temperatures, the acicular structure represented by those micrographs persisted. Specimens were cooled in molten tin at temperatures above 220°C ., and at lower temperatures in molten Wood's metal. It was found, however, that when the temperature of the cooling medium was lowered to 320°C . further lowering did not produce any pronounced change in the microstructure.

Besides the specimens quenched in lead at specified temperatures, one specimen, 28 in. long, was cooled in a tall bath of lead which varied in temperature from 340°C . at the top to about 380°C . at the bottom. Along the length of this specimen the gradual modification of the structure could be followed.

The structures of this group are very similar to the types obtained by cooling in water or oil. They are illustrated by Figs. 40 to 42 (Plate XLVII.).

The structures described in the preceding sections represent certain phases of the gradual change in structure that accompanies a progressive lowering of the temperature of the cooling medium. The micrographs included in a single group do not represent all the possible variations of structure that properly belong to the group, and the seven groups into which the structures have been divided do not represent the complete range of structures obtainable. Nevertheless, the series of micrographs which accompany this paper are sufficient to illustrate the main features of the sequence of structures obtained by progressive lowering of

the temperature of the cooling medium. The principal features of the structures of each group are summarised in Table II.

TABLE II.—*Summary of Microstructures.*

Type of Structure.	Illustrated by—	Summary of Structure and Constitution.
Group 1	Figs. 1 and 2	Normal pearlite, and structures closely resembling it, in which the laminations arising from one grain of austenite adopt more than one orientation.
Group 2	Figs. 3 to 7	Structures constitutionally similar to pearlite and formed as a result of the eutectoid reaction, but characterised by the fan-like arrangement of the uniformly laminated areas.
Group 3	Figs. 8 to 12	Structures formed when the eutectoid reaction is suppressed and the decomposition of austenite is initiated by the γ - α change. The symmetry of this structure is related to two sets of planes in the original austenite grains.
Group 4	Figs. 13 to 22	Structures formed in the same way as those of Group 3, but at a lower temperature. The symmetry of these structures is related to three sets of planes in the original austenite grains.
Group 5	Figs. 23 to 30	Structures formed in the same way as those of Groups 3 and 4 and related to three sets of planes in the original austenite grains. The symmetrical pattern in Group 5 is finer and sharper than in Group 4, and is formed at a lower temperature.
Group 6	Figs. 31 to 39	Similar structures to those of Groups 4 and 5, but formed at a lower temperature and definitely acicular.
Group 7	Figs. 40 to 42	Structures formed in the same way as those of the preceding groups, and establishing the connection between the intermediate structures included in those groups and martensite.

Pearlite is known to consist of alternating plates of ferrite and cementite; as the rate of cooling is increased its characteristic lamellar arrangement persists, but the relation of the laminations to the original austenite grain changes. The progressive alteration in the symmetry of the pearlite grains may be followed from the normal pearlite to the fan structure, and when the fans

are large the characteristic ferrite-cementite laminations may be recognised. It is therefore evident that all the structures included in Groups 1 and 2 must have almost the same constitution and mode of origin. Even when the fans are irresolvable it is reasonable to suppose that they are constitutionally similar to the large resolvable fans.

Between the fan structures of Group 2 and the random, finely laminated structures of Group 3, there is a discontinuous change in symmetry. The structures of Groups 4, 5, and 6 are evidently related to those of Group 3, and it may be said that although this structure is progressively modified as the temperature at which the austenite decomposes is lowered, the successive stages in this modification are so closely related that the transition is gradual. There is evidently only one discontinuous change, that is, between the structures of Group 2 and those of Group 3; on either side of this break in the sequence the variation is gradual.

The structures in Groups 4, 5, and 6 are closely related; nevertheless it is certain that none of these types occurs in association with any structures not closely resembling them. Thus, structures of Group 4 are never found in specimens composed mainly of structures of Group 6, and structures of Group 6 are never found associated with the vague acicular structures obtained with faster rates of cooling.

The fan structures of Group 2 may be obtained, however, in association with any structure formed at a lower temperature—that is, they may be obtained in association with structures of Groups 3, 4, 5, 6, and 7, or with the fine acicular structure. The amount of the fan structure associated with other structures bears no relation to the position of those others in the series; in other words, it is not observed that large quantities of fans occur in association with Group 3 structures, and gradually diminishing quantities with structures of Groups 4, 5, 6, and 7. Actually, the occurrence of the fan structure is not related in any way to the others; specimens composed of structures of Groups 3, 4, 5, 6, and 7 may be obtained without fans, and under slightly different conditions varying quantities of the fan structure may be obtained in association with any other structure.

In the specimens from which the micrographs of the structures of Groups 3, 4, 5, 6, and 7 were taken examples of fans were

not conspicuous, but in other series of specimens of this steel fans were observed. The occurrence of fans in association with other structures was most commonly observed in specimens of larger diameter or of higher carbon content.

THE RELATION OF THE STRUCTURES TO THE THEORY OF HEAT TREATMENT.

Starting from pearlite, the gradual change in structure may be traced until the practically irresolvable fan structure is obtained. This continuous series of structures evidently corresponds with the progressive lowering of the Ar' point with an increase in the rate of cooling. Starting from the structures of Group 3, the gradual change may be traced until the small acicular structure characteristic of rapidly cooled steels is obtained. This continuous series of structures evidently corresponds with the progressive lowering of the Ar'' point with an increase in the rate of cooling.

The structures of Groups 3, 4, 5, and 6 do not occur when any of the common methods of varying the rate of abstraction of heat are used, and a comparison of the conditions realised and the results obtained by these methods with those of the present work illustrate certain aspects of the relations between the Ar' and Ar'' points.

Three methods of varying the rate of cooling are available : (a) by varying the size of the specimen while using a constant cooling medium ; (b) by varying the initial temperature while keeping every other factor constant ; and (c) by varying the temperature of the cooling medium.

The conditions realised when the rate of cooling is varied by changing the size of the specimen are very complex, and the conditions at the outside of large specimens are very different from those at the centre. Nevertheless, the sequence of structures obtained in this way is a rough indication of the effect of cooling at different rates from the initial temperature to that of a medium held at a low temperature. When the specimen is large and cooling is accomplished by quenching in water, the structure at the centre of the specimen may be some modification of the Ar' structure illustrated in the micrographs of Groups 1 and 2. This type

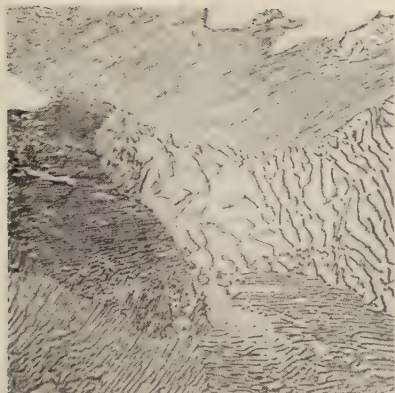


FIG. 1.—Specimen *A*, cooled in furnace. $\times 820$.

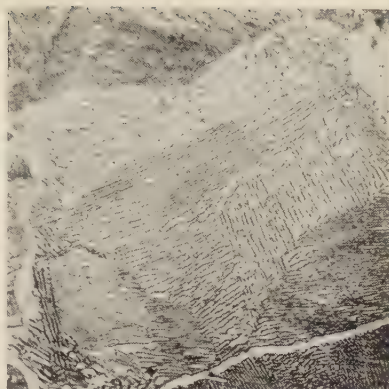


FIG. 2.—Specimen *B*, rapidly cooled in furnace. $\times 820$.

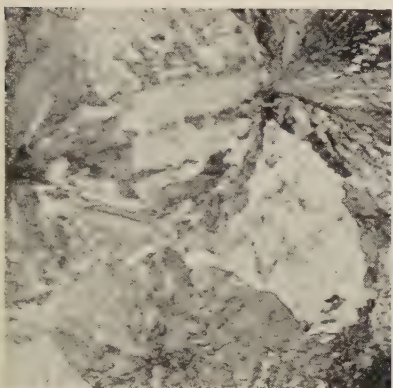


FIG. 3.—Specimen *C*, rapidly cooled in furnace. $\times 430$.

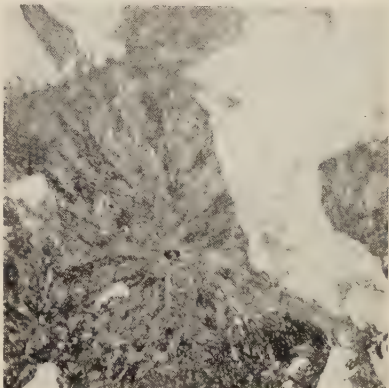


FIG. 4.—Specimen *C*, rapidly cooled in furnace. $\times 430$.



FIG. 5.—Specimen *D*, cooled in molten metal at 480°C . $\times 820$.



FIG. 6.—Specimen *D*, cooled in molten metal at 480°C . $\times 820$.

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FIG. 7.—Specimen *E*, cooled in molten metal at 400° C. $\times 820$.

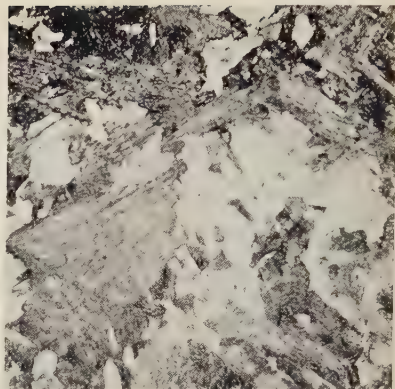


FIG. 8.—Specimen *F*, cooled in molten metal at 420° C. $\times 430$.



FIG. 9.—Specimen *F*, cooled in molten metal at 420° C. $\times 430$.



FIG. 10.—Specimen *F*, cooled in molten metal at 420° C. $\times 430$.

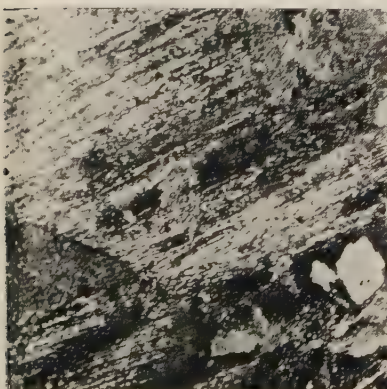


FIG. 11.—Specimen *F*, cooled in molten metal at 420° C. $\times 820$.



FIG. 12.—Specimen *F*, cooled in molten metal at 420° C. $\times 820$.

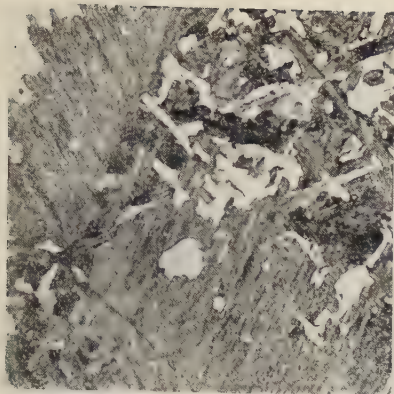


FIG. 13.—Specimen *H*, cooled in molten metal at 400° C. $\times 430$.



FIG. 14.—Specimen *H*, cooled in molten metal at 400° C. $\times 430$.

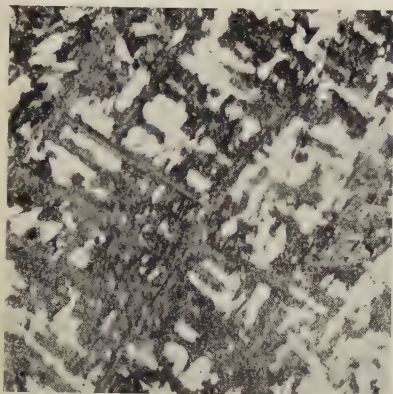


FIG. 15.—Specimen *I*, cooled in molten metal at 400° C. $\times 430$.

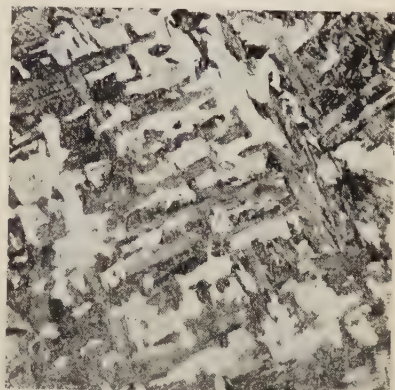


FIG. 16.—Specimen *I*, cooled in molten metal at 400° C. $\times 430$.



FIG. 17.—Specimen *I*, cooled in molten metal at 400° C. $\times 430$.

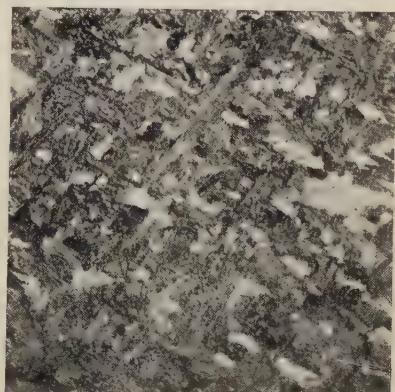


FIG. 18.—Specimen *H*, cooled in molten metal at 400° C. $\times 430$.

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FIG. 19.—Specimen *H*, cooled in molten metal at 400° C. $\times 820$.

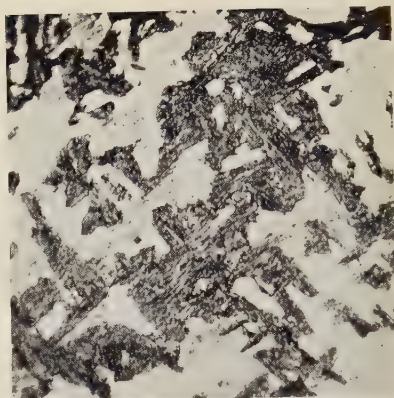


FIG. 20.—Specimen *G*, cooled in molten metal at 410° C. $\times 820$.

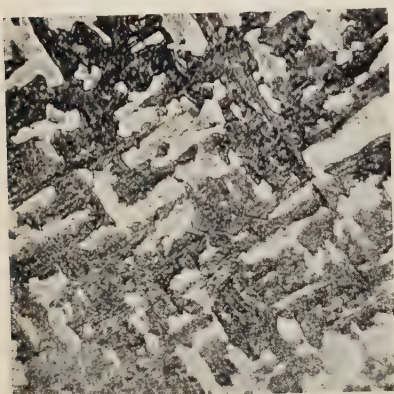


FIG. 21.—Specimen *H*, cooled in molten metal at 400° C. $\times 820$.



FIG. 22.—Specimen *G*, cooled in molten metal at 410° C. $\times 820$.



FIG. 23.—Specimen *J*, cooled in molten metal at 390° C. $\times 430$.



FIG. 24.—Specimen *J*, cooled in molten metal at 390° C. $\times 430$.

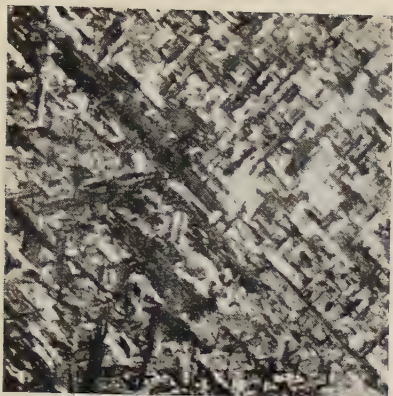


FIG. 25.—Specimen *J*, cooled in molten metal at 390° C. $\times 430$.



FIG. 26.—Specimen *J*, cooled in molten metal at 390° C. $\times 430$.



FIG. 27.—Specimen *J*, cooled in molten metal at 390° C. $\times 820$.



FIG. 28.—Specimen *J*, cooled in molten metal at 390° C. $\times 820$.

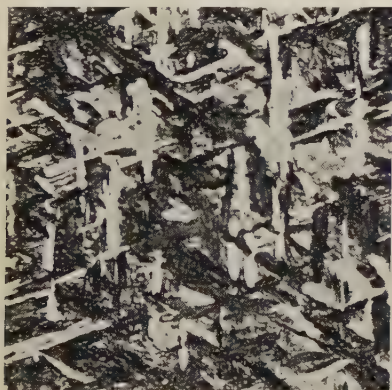


FIG. 29.—Specimen *J*, cooled in molten metal at 390° C. $\times 820$.

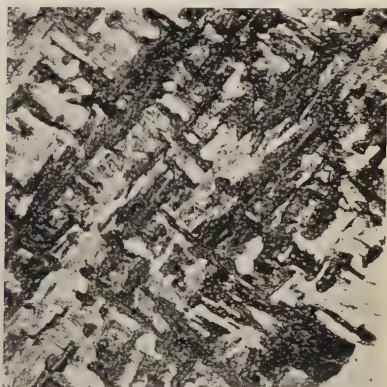


FIG. 30.—Specimen *J*, cooled in molten metal at 390° C. $\times 820$.

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FIG. 31.—Specimen *K*, cooled in molten metal at 380° C. $\times 430$.



FIG. 32.—Specimen *K*, cooled in molten metal at 380° C. $\times 430$.

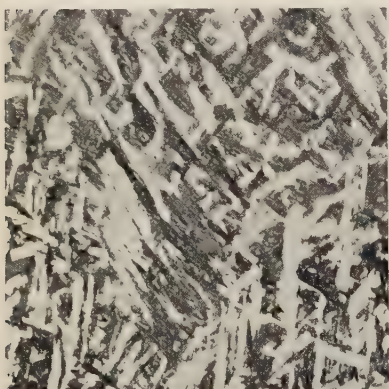


FIG. 33.—Specimen *K*, cooled in molten metal at 380° C. $\times 430$.



FIG. 34.—Specimen *K*, cooled in molten metal at 380° C. $\times 430$.



FIG. 35.—Specimen *L*, cooled in molten metal at 380° C. $\times 820$.



FIG. 36.—Specimen *L*, cooled in molten metal at 380° C. $\times 820$.

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FIG. 37.—Specimen *L*, cooled in molten metal at 380° C. $\times 820$.



FIG. 38.—Specimen *L*, cooled in molten metal at 380° C. $\times 820$.



FIG. 39.—Specimen *L*, cooled in molten metal at 380° C. $\times 820$.



FIG. 40.—Specimen *N*, cooled in molten metal under temperature gradient varying from 340° to 380° C. $\times 430$.

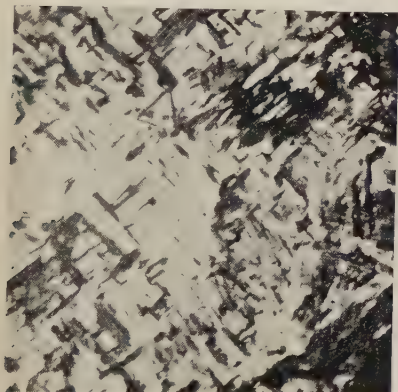


FIG. 41.—Specimen *N*, cooled in molten metal under temperature gradient varying from 340° to 380° C. $\times 430$.



FIG. 42.—Specimen *N*, cooled in molten metal under temperature gradient varying from 340° to 380° C. $\times 430$.

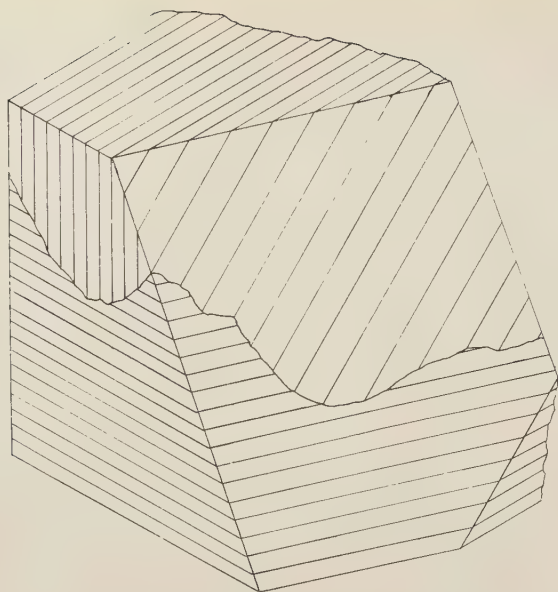


FIG. 43.—Diagram illustrating the arrangement of laminations in a single grain of austenite.

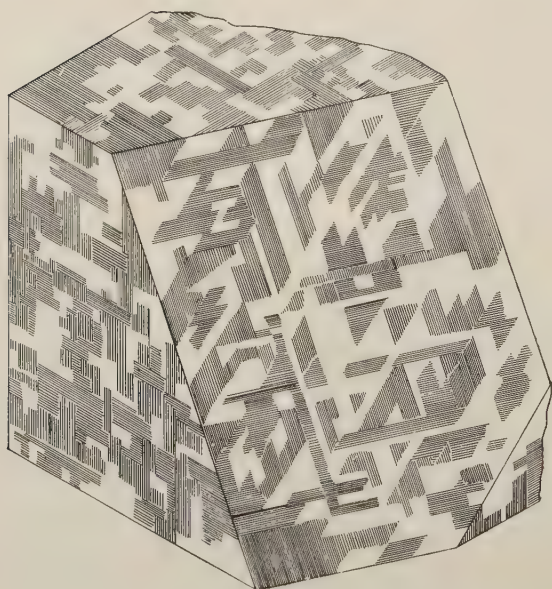


FIG. 44.—Diagram illustrating how the direction of the laminations determines the appearance of the section through a grain.

of structure persists over a range of specimens of different size, but when a certain rate of cooling is reached small quantities of Group 7 structures are associated with fens. As the size of the specimen is further decreased, the entire structure at the centre becomes similar to those of Group 7.

The method of varying the rate of cooling by altering the initial temperature is not very effective, and it has been used chiefly under conditions that produce a change in the constitution of the steel with each change in the initial temperature, as, for instance, in the work described by Lucas,⁽¹⁴⁾ and in the numerous investigations of the effect of initial temperature on alloy steels. When the lowest initial temperature is sufficiently high to ensure that the steel consists entirely of uniform austenite at the moment of quenching, then raising the initial temperature may produce results similar to those obtained by varying the size of the specimen.

The third method of varying the rate of cooling is that used in the present work. The results obtained by this method depend on the size of the specimen and on the range through which the temperature of the cooling medium is varied. Hitherto, when this method has been used, the medium employed has been water or oil maintained at various fairly low temperatures, because it has generally been thought that low temperatures are necessary to suppress the Ar' change. The temperature at which the medium must be held in order to suppress the Ar' transformation depends, however, on the size of the specimens, and when the specimens are small the change may be suppressed by cooling in media at moderately high temperatures.

With media maintained at fairly low temperatures, the results obtained by varying the temperature are similar to those obtained with the other methods of cooling. If the specimen is large enough, and the maximum temperature of the medium sufficiently high, the eutectoid reaction takes place; as the temperature of the medium is lowered the change is split, and eventually the complete transition occurs at Ar'' .

The results obtained by all the foregoing methods of varying the rate of abstraction of heat are similar, and the recent theories of heat treatment are based on the results obtained in this way. These methods of varying the rate of cooling differ from that used

in the present work, because, with all these methods, the Ar'' change takes place before the temperature of the cooling medium is reached. In other words, the rate of cooling necessary to suppress Ar' is maintained throughout the entire range of temperature. This is not strictly true, for the rate of cooling measured in degrees cooled per second actually becomes progressively slower as the temperature of the cooling medium is approached, but this fact need not be taken into account at present, although it undoubtedly exerts a pronounced effect on the Ar'' change. For the present purpose, it is sufficient to know that with the customary methods of cooling the rate of cooling before and during the Ar'' transformation is proportional to the rate of cooling required to suppress the Ar' change.

In the present work small specimens were used, and it was found that Ar' could be suppressed by cooling in molten tin at any temperature below 420° C. When, therefore, a specimen was immersed in tin at 400° C., Ar' was suppressed, but the rate of cooling necessary to accomplish this was not maintained. Instead, the rate of cooling became considerably slower as the steel approached the temperature of the medium, and cooling practically ceased when that temperature was attained. When the rate of cooling was thus retarded the Ar'' change took place, and the structures of Groups 3, 4, 5, and 6 were produced.

From the foregoing comparison of the results obtained with the different methods of varying the rate of cooling, the following general statement may be formulated: A rate of cooling that is sufficiently rapid to suppress or interrupt the Ar' change is also rapid enough to lower Ar'' to a low temperature. Consequently, when the steel is cooled in such a way that the rate of cooling necessary to suppress Ar' is maintained, Ar'' takes place at a low temperature, and the product of the change is determined by this fact. If, however, Ar' is suppressed by cooling rapidly through the appropriate range of temperature, and the rate of cooling is then reduced, the Ar'' change takes place, and the product of the change depends on the temperature at which the retardation of cooling becomes effective. Ar'' is therefore a change that may be progressively lowered by increasing the rate of cooling, and the product of the change depends on the temperature at which it takes place.

It has already been stated that there is a distinct break in the continuity of the structures between those of Group 2 and those of Group 3. This break is marked by a complete change in the crystallography of the structures, but it does not appear to be accompanied by any sudden change in their ultimate constitution. The structures of Groups 3 and 4 are composed of minute laminations, and there is no reason to suppose that these laminations are not alternate plates of ferrite and cementite.

At the normal temperature of the transition, austenite decomposes into α -iron and cementite; the ferrite contains a small quantity of carbon in solution. At very low temperatures austenite transforms more or less completely to a solid solution of carbon in α -iron. Between ferrite and this solid solution formed at low temperature, there is no essential difference—except the amount of carbon retained in solution—and both forms of this constituent may be called α solid solution.

Returning to the discussion of the constitution of the structures formed at different temperatures, there does not appear to be any sudden change in the constitution of the structures between Group 2 and Group 3, and there is no reason to suppose that there is any constitutional discontinuity at any point in the continuous series of structures between Group 3 and Group 7. From the structures of Group 3 to those formed by water-quenching, the gradual transition may be traced, and there is every reason to believe that the ultimate constitution of the observed structures also varies gradually as the temperature at which they are formed is lowered.

If there is no discontinuous change in the ultimate constitution of the structures formed from austenite at different temperatures, the transition from the aggregate pearlite, formed at the normal temperature of the change, to the solid solution formed at low temperatures must be gradual. In other words, as the temperature at which the austenite decomposes is progressively lowered, the amount of carbon retained in solution in the α -iron increases, and the amount of cementite formed decreases. The ultimate constitution of the product depends entirely on the temperature of the transformation; it does not matter whether the change is the Ar' or the Ar'' , and the constitutional difference between the structure of Groups 3 or 4 and those of

Group 2 is simply related to the difference between the respective temperatures of formation.

The Nature of the Ar' and the Ar'' Transformations.

It appears that the ultimate constitution of the product of the decomposition of austenite varies progressively with the temperature at which the transformation occurs. If it were possible to lower the transformation temperature in a perfectly gradual manner, a continuous variation in the product would result. The actual lowering of the temperature of the transformation with an increase in the rate of cooling is discontinuous, however, and this discontinuous lowering is accompanied by a sudden break in the crystallographic sequence of the structures obtained. This break in the sequence of structures corresponds to the distinction between the Ar' and the Ar'' changes, and what requires to be explained with regard to these two changes is the difference in their response to a variation in the rate of cooling, the crystallographic difference of the structures produced, and the fact that when the temperatures at which the two changes take place are not too widely separated the ultimate product of the changes is approximately the same.

The change from austenite to pearlite involves two separate reactions, which under normal conditions take place simultaneously. The formation of ferrite and of cementite are mutually dependent changes; under certain conditions, if the formation of ferrite begins, that of cementite must follow, and if the formation of cementite begins, that of ferrite must follow. Under normal conditions the formation of pearlite may be initiated either by the formation of ferrite or of cementite; this is the Ar₁ change. When the rate of abstraction of heat is increased, however, and the change does not take place at the temperature or under the conditions represented by the iron-carbon diagram, the two reactions involved in the Ar₁ change may be differently affected.

In the opinion of the author, the difference between the Ar' and the Ar'' change is simply that the Ar' is the decomposition of austenite initiated by the formation of cementite, whereas the Ar'' is the decomposition of austenite initiated by the formation

of α solid solution. For a given increase in the rate of cooling, the change from γ -iron to α -iron is lowered to a greater extent than the formation of cementite. Consequently, once the normal rate of cooling is exceeded, the decomposition of the austenite is always initiated by the cementite, and the crystallographic form of the structures of Group 2 is determined by the crystal habit, under the imposed conditions, of cementite. The composition of cementite remains constant, whatever the temperature of its formation. As a result, the rate of formation of cementite is determined by the rate of diffusion of the carbon and by the number of centres from which the growth of cementite begins. To a certain extent the rate of formation of cementite increases as the rate of cooling increases, therefore the Ar' change takes place completely as the rate of cooling is increased from furnace cooling to cooling in lead at a temperature of 440° C. With faster rates of cooling, however, the rate of abstraction of heat exceeds the rate of formation of cementite, and the Ar' change is interrupted and ultimately suppressed.

A rate of cooling sufficiently rapid to suppress the Ar' transformation is also sufficiently rapid to prevent the formation of cementite at lower temperatures, and if no other factor intervened the austenite would cool unchanged to the ordinary temperature. In fact, however, the decomposition of austenite at lower temperatures is initiated by the γ - α change, and this change is able to take place at lower temperatures than the formation of cementite, because the composition of the α solid solution alters with the temperature at which it is formed. The farther austenite is cooled below the temperature at which it is normally stable, the more unstable it becomes; therefore it can change to α -iron in the presence of increasing quantities of carbon. This increase in the amount of carbon retained by the α -iron offsets the decrease in the rate of diffusion at low temperature; consequently the change from γ -iron to α -iron can take place at temperatures and under conditions that prevent the formation of cementite.

The general difference between the formation of cementite and the γ - α change may be stated as follows: For a given increase in the rate of cooling, the allotropic change is lowered to a greater extent than the formation of cementite. Because the composition of cementite remains constant, its formation is

lowered, interrupted, and suppressed by increasing the rate of cooling. Because the amount of carbon retained in solution by the α -iron increases as the temperature falls, this change is progressively lowered, but it is not interrupted or suppressed by the rate of cooling.

The crystallographic form of the product of the decomposition of austenite depends on the manner in which the change is initiated ; its ultimate constitution depends on the temperature at which the change takes place, and the rate of abstraction of heat while the change is in progress. Thus, at the normal temperature of the change, the ultimate composition of the product is α -iron and cementite. As the temperature of the transformation is progressively lowered, more carbon is retained in solution in α -iron, and less separates as cementite. When the change takes place at a low temperature and during rapid abstraction of heat, no cementite can form, and the austenite must change completely to α solid solution or remain unaltered.

THE CRYSTALLOGRAPHIC FORM OF THE STRUCTURES FORMED AT THE AR" POINT.

The crystallographic form of the structures of Groups 3 to 7 is determined by the crystal habit of α -iron and by the conditions under which the change takes place. In the normal ferrite-pearlite structures obtained by cooling at annealing rates, the connection between the crystallographic planes in the austenite and the allotropic change is not very evident, and it might be supposed that there was no crystallographic connection between the annealed structure in hypo-eutectoid steels and the structures of Groups 3 to 7. This apparent discontinuity is due to the fact that the structures formed are influenced by other factors besides the crystal habit of the α -iron.

The structures of Groups 4 to 7 are forms of the Widmanstätten structure, and many of the micrographs of Groups 4 and 5 resemble the structures found in meteorites, ingots, and steel castings. The type of Widmanstätten structure formed during very slow cooling consists of ferrite and pearlite, and its formation depends on two factors : (1) the crystal habit of the α -iron, which tends to form along the crystallographic planes in the

austenite, and (2) cooling through the critical range at such a rate that solid diffusion is able to maintain a perfectly uniform distribution of carbon in the residual austenite.

The ferrite-pearlite structures of annealed steels are formed under conditions which require that considerable quantities of carbon rejected by the α -iron shall be absorbed by the remaining austenite, and the rate of cooling is too rapid to permit this carbon to be uniformly distributed in the austenite. The ferrite, instead of forming along the crystallographic planes, actually grows along the concentration gradient. It is this fact which determines the crystal structure of steels cooled at annealing rates.

The Widmanstätten structure is again obtained when more rapid cooling is used, and under these conditions its formation depends on the following factors :

(1) When the first sheet of α solid solution is formed, the carbon rejected by the α -iron immediately separates from solution and forms cementite.

(2) The α -iron retains most, or all, of the carbon in solution.

It may therefore be said that the true crystal habit of the α -iron is observed with very slow cooling, because complete diffusion of carbon takes place, and with rapid cooling, because the austenite is not required to absorb to any extent the carbon rejected by the α solid solution, but it is not observed with ordinary annealing rates of cooling because considerable quantities of carbon are transferred to the residual austenite, and complete diffusion of this carbon is not permitted. The Widmanstätten structure formed with very slow cooling or with rapid cooling corresponds to the normal crystal habit of α -iron ; the common ferrite-pearlite structures formed in annealed steels are the abnormal structure.

The structures of Groups 3, 4, 5, and 6 are ultimately composed of minute plates of α solid solution and cementite. These laminations cannot be seen in the structures of Group 6, but it must be inferred from the observed facts that such plates are the ultimate units of the structure. Similar laminations have been observed by Lucas⁽¹⁶⁾ in the dark lenticular markings that occur in quenched high-carbon steel.

The pattern shown in the structures of Groups 3 to 6 depends on the relation of the surface examined to the direction of the

minute laminations. Areas in which the laminations are at right angles to the surface examined etch darkly ; as the angle between the laminations and the surface examined decreases, the areas etch more lightly, and areas in which the laminations are inclined at a very small angle to the surface examined remain white.

The structures of Group 3 appear to be formed on two sets of planes in each austenite grain, and the solid austenite grain must therefore be as illustrated in Fig. 43 (Plate XLVIII.), which shows the arrangement of laminations in a single grain, assuming the formation of these laminations to be related to two sets of planes at right angles.

In the structures of Groups 4 to 6 each grain shows a definite symmetrical pattern, the exact appearance of which depends on the relation of the surface examined to the symmetry of the grain. Figs. 14 to 18 (Plate XLIII.), for example, represent different sections of approximately similar solid grains ; to obtain a correct picture of the structure, it would be necessary to construct a solid grain from the observation of different random sections. Though this is impossible, it is still possible to deduce certain facts concerning the solid grain from the observation of these random sections. In Fig. 15, for example, a definite contrast between black and white areas is shown, and if this contrast were due to a constitutional difference between these areas it would persist in all sections throughout the grain. The contrast between black and white does not persist, however, when different sections of the grain are examined ; there is, in fact, a complete change in the etching contrast, as is illustrated by Figs. 16 to 18. It follows, therefore, that the differently tinted areas which compose the pattern of a single grain are not areas of different constitution ; they are simply the same type of area examined at a different angle. With the exception of the variation in constitution between the minute laminae forming the ultimate components of the structure, the solid grain is constitutionally uniform. The laminations are oriented parallel to three sets of planes, and the appearance of the grain as a whole depends on the relation of the surface examined to the three sets of planes controlling the orientation of the laminations. Fig. 44 (Plate XLVIII.) illustrates how the direction of the laminations determines the appearance of a section through a grain.

The structures of Groups 3, 4, 5, and 6 are formed at a constant temperature under conditions that permit the formation of cementite laminae. Structures formed while the temperature is falling rapidly, or under conditions that do not permit the formation of cementite laminae, have certain different characteristics. Thus, the appearance of a section through the grains of Groups 3 to 6 is determined by the relation of the section to the direction of the minute laminations. If, however, these laminations consisted entirely of α solid solution, the appearance of an area would not alter with the direction of the section. Thus, in the structures formed at very low temperatures the patterns are not so clear. In the structures of Group 7 the black and white markings are probably due to the fact that the black areas were formed at a higher temperature than the white.

SUMMARY.

By cooling small steel specimens in molten metal at various temperatures between 600° C. and 220° C., the sequence of structures obtained when austenite is caused to decompose at progressively lower temperatures has been investigated.

The ultimate composition of the product of the decomposition of austenite appears to vary gradually as the temperature at which the transition takes place is lowered. When the transition takes place at the normal temperature the product consists of α -iron and cementite. As the temperature of the transition is lowered, more carbon is retained in solution in α -iron, and less separates as cementite.

The crystallographic form of the product of the decomposition of austenite depends on whether the decomposition is initiated by the allotropic change or by the formation of cementite. The Ar' change is initiated by cementite, and the series of structures obtained at Ar' is determined by this fact. The Ar'' transformation is initiated by the allotropic change, and the structures formed at this change point are related to the crystallographic planes of the austenite.

The relations between the Ar' and Ar'' points are determined by the fact that the allotropic change and the formation of cementite are differently affected by variations in the rate of cooling. The formation of cementite is slightly lowered,

interrupted, and suppressed by a progressive increase in the rate of cooling. The allotropic change is progressively lowered as the rate of cooling is increased. The progressive lowering of the allotropic change cannot be realised in steels containing more than 0.2 per cent. of carbon, for in these steels, with certain rates of cooling, the decomposition of the austenite is initiated by the formation of cementite, and this change must be suppressed before the initiation of the transformation by the allotropic change can again be realised. In low-carbon steels, however, the structure passes directly from ferrite and pearlite to solid solution structures, whose crystallographic form is similar to those produced when the Ar" change in high-carbon steels takes place at a high temperature.

There are two series of structures produced by increasing the rate of cooling. Within each series the variation in structure is gradual. All structures formed at Ar" may be tempered, and the tempered structure is related to the original structure, to the time and to the temperature of tempering. The structures formed by cooling at different rates cannot be obtained by tempering other structures.

So far as crystallographic form or structure is concerned, there is no relation between cooling at different rates and tempering at different temperatures. The same ultimate constitution may, however, be produced in either of two ways. When the α solid solution produced by very rapid cooling is reheated, carbon gradually separates from solution and forms cementite. By reheating to different temperatures, all variations in constitution between solid solution and ferrite-cementite aggregate may be obtained. Thus, the globular structure, formed by tempering above 600° C., may have the same ultimate constitution as the fan structure, but the crystallographic form and the general properties of these two structures are entirely different.

The results described in the present paper are part of a research on intermediate rates of cooling and their relation to wire-drawing, which is being carried out for the Wire Ropes Committee of the Safety in Mines Research Board. The metallurgical work is being done in the Royal School of Mines, and the author wishes to express his indebtedness to Professor H. C. H. Carpenter, F.R.S., under whose supervision the present work was performed.

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DISCUSSION.

Professor S. M. DIXON (London) said that for the last three years the Committee on Wire Ropes of the Safety in Mines Research Board had been examining fractures of ropes which had failed in service, and also the recapping samples taken at stated intervals from wire ropes. That examination showed there must be some correlation between the behaviour of steel ropes in service and the microstructure of the steel. The mechanical tests which could be applied to steel were not sufficient to give the knowledge that was required of steel wire. The manufacture of steel wire was one of those processes in which the art was, he ventured to say, in advance of the science, and it was desirable that our knowledge should advance rapidly in order to solve the difficulties involved in the manufacture of wire ropes. For instance, it sometimes happened that a rope which was removed from service only because it had fulfilled its statutory life of $3\frac{1}{2}$ years, apparently in good condition, was replaced by another rope which was made to exactly the same specification, as shown by the mechanical tests, yet the second rope would fail, under the same working conditions, in two years. That was a very distressing thing for the engineer, and anything which would throw light on the endurance of the wire was badly needed.

Mechanical endurance tests were very difficult to perform, and gave, up to the present, very unreliable results. The ordinary mechanical tests made in the laboratory on wire rod treated in exactly the same way as the rod treated by Dr. Robertson gave the results which one would expect. At very low temperatures, unfortunately, the experiments showed some discrepancies, but he thought those discrepancies could be explained. Between 400° and 360° C. the points obtained were rather scattered; the reason was that at that temperature of cooling the material was so very brittle that the very slightest eccentricity in the testing machine had its effect. The higher results were therefore selected as being more likely to be the correct ones. The curve showed exactly what one would expect, of course, but it was of interest to the engineer because he now found that the mechanical tests, as far as they went, confirmed the results shown in the paper. To show the relation between stress, strain, and temperature a solid diagram was required. It was even easier to observe in a solid model, in which the curves were all drawn to scale, how the stress-strain curve changed its shape in accordance with the temperature.

The important thing for the engineer was to notice that this was only a preliminary step in the investigation of hard steel wire. It was necessary to begin with the rod, but it seemed of the utmost

importance to realise that such great changes were produced by very small changes in the temperature of the lead bath. He thought that would ultimately explain some of the differences obtained in the endurance of steel wire.

Professor J. H. ANDREW (Glasgow) said he had been associated with Dr. Robertson for very many years, and had been able to follow his work right from the beginning. Dr. Robertson had, for the first time, shown a complete series of the different structures that could be obtained on quenching steel in the form of thin wires. Most people had obtained those particular structures at different times, but he thought Dr. Robertson was the first to classify them into their respective orders.

Dr. Robertson spoke of the formation of cementite as initiating the Ar' change. He believed Dr. Robertson regarded carbon as existing in solid solution in the γ -iron as such; his view was that carbon atoms existed as such and not in the form of Fe_3C . He took it, therefore, that when he (Dr. Robertson) spoke of the formation of cementite he meant what he said, and not merely the separation of cementite. That required proof. It was very difficult to reconcile a line of the shape of the *SE* line with a line denoting the formation of a compound. The form of that line would rather seem to signify an ordinary separation such as one was used to in other systems. He would like to ask whether Dr. Robertson had any proof that the carbon existed as free carbon molecules rather than as Fe_3C .

Dr. Robertson dealt with the two changes, the Ar' and the Ar". The Ar" had been well established by Mr. Lewis, but, personally, he thought the Ar' was rather doubtful, and that it was a mobile point rather than a particular fixed temperature.

With regard to the author's fan-shaped structures, it would be of interest to know whether he thought that the variation in the structure which was obtained with different quenching temperatures and quenching rates was due to the degree of strain which the specimen underwent on quenching in different media. When a specimen was quenched in cold water there was a tremendous strain. In a less drastic medium the strain would be less, probably giving fan-shaped structures.

He would like to ask the author what bearing the work described in the paper had on his (Dr. Robertson's) theory. Personally, he could not at all connect that theory of hardening with the micrographs.

Mr. J. H. WHITELEY (Consett) said that his own view was that austenite could transform in three different ways according to cooling conditions. It could change directly into lamellar pearlite; or it could change into nodular troostite; or it could transform into martensite and then into troostite. He regarded the Groups 1 and 2 described in the paper as belonging to the first method, and the

remainder to the second or third. It would have been useful if the author had tempered the latter structures in order to see how they resolved themselves. He was convinced that exceedingly fine carbide particles could move bodily, even at low temperatures, for short distances, and he thought that the minute laminations mentioned as observed in Groups 3 and 4 were due to such a movement. The precipitated carbide particles tended to arrange themselves along definite planes in the grains, and if a sufficiently high magnification and resolution could be obtained these lines would appear as a series of dots. Dr. Robertson had not stated the manganese content of the steel used in his experiments. It would have been of value if he had made a similar series of tests with a steel containing, say, 1.5 per cent. of carbon; in fact, the two could have been treated together. If the Ar' transformation were due to cementite inoculation, as was quite likely, it would be anticipated that Group 2 would appear at still lower temperatures with a higher carbon steel, since the tendency for cementite nuclei to appear should be greater. He was not clear as to what the author meant by the rate of formation of cementite. Nuclei either appeared or did not appear according to the rate of cooling. Was it the rate of crystal growth after formation that was meant?

Mr. DARTREY LEWIS (Bridgeport, Conn., U.S.A.) said Dr. Robertson's paper and his own covered the same ground; they had done a lot of things in common. It would help him if Dr. Robertson would say what were the times of the treatments in his quenching medium. To explain what he had in mind, he would say that his own work had shown that if one quenched a steel in a quenching medium at 300° C. and left it there for only half a minute before taking it out, it would still be austenitic, and on cooling down to room temperature it would change over to martensite. The structure one looked at under the microscope would not be the structure formed at 300° C. at all, but the structure formed during the cooling. On the other hand, if one left the steel in the quenching medium at 300° C. for five minutes or more, then the austenite would break down almost completely at the temperature of the quenching medium and result in a structure entirely different from that obtained if it were left in for only half a minute. It was very important, therefore, to know how long the specimens remained in the quenching medium.

Dr. ROBERTSON, in reply, thanked Professor Dixon for describing the results of mechanical tests on lead-cooled steel, which illustrated very clearly the progressive change in mechanical properties that accompanied a progressive change in the temperature of the cooling medium; they proved that the hardness produced by water-quenching was not an abnormal, disconnected phenomenon, but part of a continuous change.

He also thanked Professor Andrew for his kind remarks. As Professor Andrew had suggested, he considered that carbon was in solution as such, and not as a compound with iron. There were various reasons why he held that view, which now appeared to be generally accepted. In the first place, he could not conceive how the iron carbide could maintain its identity while in solution in iron, unless the carbon atoms remained permanently attached to the three iron atoms with which they had been associated when the carbide existed in the free state. If that condition were not realised, how would the iron atoms that belonged to the carbide be distinguished from those that did not? if that condition were realised, it would mean that wherever the carbon atoms diffused in the solid iron they would be accompanied by three iron atoms. He considered that the specific volume of carbon steels supplied experimental proof of that view, for, whereas the specific volumes of annealed steels lay on a line joining the specific volume of α -iron to that of cementite, the specific volumes of quenched steels lay very close to the line joining the specific volume of α -iron to that of graphite. That difference between the specific volumes of annealed and quenched steels could not be explained by assuming that carbon existed as carbide in both cases. Further, the expansion that accompanied the solution of carbide in austenite during heating could not be attributed to the simple solution of that compound. Professor Andrew mentioned the shape of the *SE* line as evidence that carbon existed as carbide while in solution. He (Dr. Robertson) did not see how the shape of the *SE* line could be used as an argument in that connection, and in any case, the shape of the line was not necessarily affected by the condition of the carbon while in solution; it might equally well depend on its condition when it came out of solution.

With regard to the bearing of the work described in the paper on the theory advanced, he considered that the structures described were part of the general phenomena associated with the response of steel to heat treatment, and he had tried to embody the results obtained in the general theory of heat treatment.

In reply to Mr. Whiteley, Dr. Robertson stated that the manganese content of the steel was about 0.6 per cent., and that the etching reagent, which was mentioned in the paper, was 1 per cent. nitric acid in alcohol. He had performed the same kind of treatments on steels of various carbon contents between 0.1 and 1.5 per cent., and the results obtained with the highest carbon contents confirmed Mr. Whiteley's prediction that, owing to the increased proportion of carbon, Group 2 structures should be obtained at lower temperatures. His (Dr. Robertson's) views on certain aspects of heat treatment differed somewhat from those held by Mr. Whiteley. He considered that it was not a question of a discontinuous series of changes like austenite changing to pearlite, to troostite or to sorbite, but a progressive alteration in the structure and properties with progressive

variation in the temperature at which the austenite decomposed. A further difference between his views and those of Mr. Whiteley related to the decomposition of the solid solutions. Mr. Whiteley appeared to believe that the beginning of decomposition was accompanied by the complete precipitation of the carbon as infinitely small particles of cementite, and that the subsequent formation of laminated structures took place by the aggregation and coalescence of those particles. He personally believed, however, that the beginning of decomposition was accompanied by the precipitation of a small quantity of carbon only, that the carbon formed small plates of cementite, that during subsequent decomposition those small plates grew by the deposition of further quantities of carbon from solution, and that under all conditions globules of cementite were produced from those plates in the same way as they could be produced from pearlite.

In reply to Mr. Lewis, Dr. Robertson stated that he had experimented with various times of immersion at each temperature, the times used being 1, 2, 4, and 9 min. The structures of Groups 3, 4, 5, and 6 were all formed completely at the temperature of the medium, but the structures of Group 7 were partly formed in the medium and partly during subsequent cooling.

CORRESPONDENCE.

Professor H. C. H. CARPENTER, F.R.S. (Hon. Treasurer), wrote : By cooling steel in molten metal Dr. Robertson has obtained structures of the martensitic type under conditions which permit their construction to be determined. When formed at high temperature (400° C.), these structures evidently consist of plates of ferrite and cementite arranged in conformity with the crystallographic planes in the austenite, and the interpenetration of the different sets of laminations forms the symmetrical grains. All the structures are three-dimensional, and it is only those of a very simple type that do not vary in appearance according to the direction in which they are cut. The author has done well to emphasise this fact and to show how the symmetrically constructed grains vary in appearance when cut at different angles.

There is no doubt that the structures of Groups 4, 5, and 6 are of the martensitic type, and although this is gradually modified, both as regards morphology and constitution, as the rate of cooling is increased, its essential features persist. As Dr. Robertson has pointed out, the structures of Groups 4 and 5 are very similar to the Widmanstätten structure obtained under certain conditions during slow cooling ; in fact, the only difference between the two types of structures is that in the ordinary Widmanstätten structure the grains are composed of a framework of ferrite parallel to the crystallographic planes in the

austenite and a matrix of pearlite, whereas in the structures of Groups 4 and 5 the grains are composed of different sets of ferrite-cementite laminations. There is clearly some connection between these structures, and this is the crystal habit of the α -iron. This leads to the conclusion that there is nothing abnormal or peculiar about the martensitic structure; it is the normal type of structure, and is produced whenever the change takes place in such a way that the crystal habit of the α -iron is the controlling factor.

In the theoretical interpretation of the effects of heat treatment it has been customary to disregard some of the implications of the iron-carbon diagram. This diagram represents exactly the relations between iron and carbon during slow cooling, but this does not exhaust its application, and there is much in the present paper to show that it also indicates the qualitative effects of varying the rate of cooling. In other words, a progressive increase in the rate of cooling is accompanied by a gradual modification of the diagram, and the product of the decomposition of austenite is determined by the temperature at which it decomposes and by the manner in which the change is initiated. In a particular steel, as the temperature of the transformation is lowered more carbon is retained in solution and less separates as cementite, and the constitution of the steel gradually alters from an aggregate of ferrite and cementite to a solid solution of carbon in α -iron. The structure varies with the constitution, but these two factors are not absolutely interdependent. The structure also depends on the part played by the grain boundaries, the amount of diffusion that accompanies the change, and whether cementite and ferrite are forming simultaneously or not.

Martensite is the result of two coincident factors. Its constitution is determined by the fact that at low temperatures the allotropic change can take place with the carbon still in solution. Its structure is determined by the fact that under the conditions of its formation the crystal habit of the α -iron is the controlling factor. The hardness of martensite—that is, its resistance to plastic deformation—is related to its structure and its constitution. It is probable that the hardness of solid solutions of carbon in α -iron increases with the carbon content, and when it is remembered that each grain of austenite is transformed into a structure consisting of innumerable minute plates of a solid solution, oriented in various directions and generally alternating with films of cementite, it is natural that the material is practically incapable of plastic flow.

Dr. ROBERTSON thanked Professor Carpenter for his remarks, and stated that he was in entire agreement with his (Professor Carpenter's) suggestions concerning the relations of the work to the iron-carbon diagram, and to the formation, structure, and mechanical properties of martensite.

THE TRANSFORMATION OF AUSTENITE INTO MARTENSITE IN A 0.8 PER CENT. CARBON STEEL.*

By DARTREY LEWIS, M.MET. (BRIDGEPORT, CONNECTICUT).

INTRODUCTION.

DURING the course of an investigation of the effect of the temperature of the quenching oil upon the properties of a 0.8 per cent. carbon steel, curiosity led to the trying of temperatures of the quenching medium higher than could be obtained with oil, and some experiments were made in which the specimens were quenched in molten tempering salt. It was found that specimens quenched in salt at 232° C. (450° F.) were, on withdrawal from the salt, non-magnetic and soft, but that on cooling in air they became strongly magnetic and extremely hard and brittle. Fig. 5, *A* (Plate XLIX.), shows a specimen which was quenched from 816° C. (1500° F.) in salt at 232° C. (450° F.). It was then taken out of the salt and bent to the curved shape shown in Fig. 5, *B*. It then cooled in air to room temperature, when a second attempt to bend it caused a completely brittle fracture, as shown in the photograph. In another experiment with the same heat treatment, the Rockwell hardness was quickly measured immediately after withdrawing from the salt, and again after cooling to room temperature. The Rockwell hardnesses hot were C-24 and C-26 (approximate Brinell hardness, 260), and cold C-58 and C-60 (approximate Brinell hardness, 650).

That steel of this composition could be quenched to comparatively stable austenite which transformed into extremely hard martensite by quite slow cooling was unexpected. At that time pressure of other work prevented further investigation, but later the work described in this paper was carried out. So far it has only been possible to work with one steel, but it is expected to extend the work to other steels as soon as possible.

* Received February 14, 1929.

In consequence, this paper should be regarded as a progress report on a new way of investigating the martensite or Arⁿ transformation.^(1, 2) The main conclusions of the paper, however, have been checked in three steels of similar composition to ensure that the results were not peculiar to the steel used.

PROGRAMME OF INVESTIGATION.

The steel investigated had the following composition :

Carbon.	Manganese.	Silicon.	Phosphorus.	Sulphur.	Chromium.	Nickel.	Copper.
0.79	0.45	0.22	0.010	0.023	0.09	0.01	0.06 per cent.

It was of basic open-hearth origin, and had been hot-rolled to 5-gauge rod and drawn one hole to 0.192-in. diam. wire.

Pieces of this wire were heated and then quenched in molten salt at various temperatures. Either $\frac{1}{2}$ min. or 5 min. in the salt was given, and the pieces were then allowed to cool in air to room temperature, during which cooling records were made of changes of length and magnetic properties. Owing to the salt freezing it could not be used for temperatures below 149° C. (300° F.), and therefore a slightly different technique was employed for these temperatures. The wire was quenched in salt at 232° C. (450° F.) for $\frac{1}{2}$ min., as before, in order to retain the same rate of quenching through the upper critical range, and was then transferred to the oil at the temperature required for 5 min. It was then cooled in air to room temperature as before.

DESCRIPTION OF THE APPARATUS.

Heating Furnace.—A Leeds and Northrup “hump” furnace was used ; it was automatically controlled, and it maintained the quenching temperature at 816° C. \pm 5° C. (1500° F. \pm 9° F.). The wire specimen was held in a 16 B. & S. gauge chromel non-magnetic wire holder, and was heated in the furnace for 4 min. ; 2 min. were required for the outside of the wire to reach the temperature of the furnace.

Salt and Oil Baths.—An electrically heated salt pot containing a commercial nitrate-nitrite drawing salt which melted at about 143° C. (290° F.) was used. The temperature was measured by a thermometer up to 316° C. (600° F.) and then by a thermo-

couple. The oil was electrically heated, and its temperature was measured by a thermometer.

Dilatometer.—A photograph of the dilatometer is shown in Fig. 6 (Plate XLIX.). Changes of length were indicated by an "Ames" dial gauge graduated in ten-thousandths of an inch. The specimens were $5\frac{1}{2}$ in. long. The upper ends were pointed to fit into a hole in the end of the stem of the dial gauge, and the lower ends were ground hemispherically and rested on a piece of thin strip steel clamped between two pieces of asbestos board. The specimens could be placed in the dilatometer and the first readings taken within 15 sec. The dilatation curves were plotted on the basis of the length of the specimens 15 sec. after their removal from the quenching medium.

Magnetic Apparatus.—The magnetising coil used is shown in the photograph of the dilatometer, Fig. 6. This coil formed part (L1)

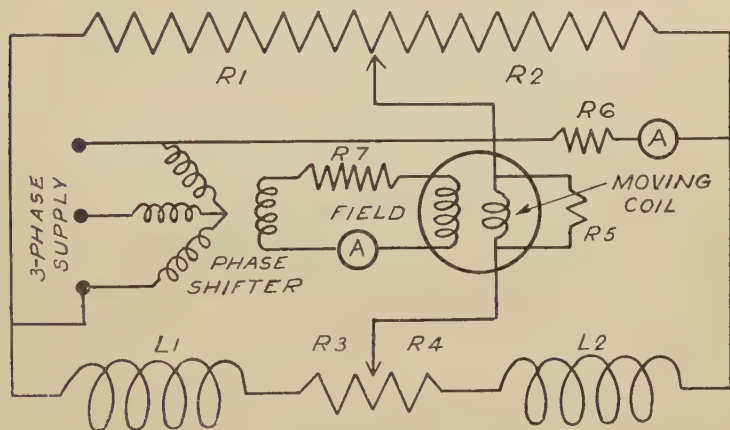


FIG. 1.—Alternating Current Bridge.

of the alternating current bridge shown in Fig. 1. A weak magnetising field was used. The bridge was completely balanced with no specimen in the coil L1. The phase of the field current of the galvanometer was adjusted by means of the phase shifting transformer, so that a change of R3 and R4 produced no deflection. With this adjustment the galvanometer deflection measured the change of inductance of the coil L1 when the specimen was introduced into it, but it was insensitive to changes of resistance

of *L1*. In other words, the deflection of the galvanometer was proportional to the intensity of the magnetisation of the specimen. The sensitivity of the galvanometer was adjusted by means of *R5*, so that the deflection of a standard specimen was constant for all experiments.

PRESENTATION AND DISCUSSION OF RESULTS.

As previously explained, the specimens were quenched in salt at various temperatures, and then air-cooled. In Figs. 2 and 3 the changes of length and intensity of magnetisation during the air-cooling are plotted against the cooling time in minutes. In all cases the temperature of the wire was below 35° C. (95° F.) at the end of 10 min.

Salt at 232° C. (450° F.). (*Fig. 2*).—On air-cooling, an expansion occurred which continued to room temperature. Also, the steel was practically non-magnetic at 232° C. (450° F.), but it became increasingly magnetisable on cooling. The micro-structure after cooling was martensitic, as is shown in Fig. 7 (Plate L.). Apparently the steel was austenitic after quenching at this temperature, and changed to martensite during the air-cooling. Furthermore, the austenite had some degree of stability, because there was no difference between the curves after $\frac{1}{2}$ min. and 5 min. in the salt. The steel quenched at 232° C. (450° F.) may be compared with Hadfield's manganese steel quenched at 20° C. (68° F.); both are austenitic, and may be converted to martensite by cooling.

The work of a number of investigators ^(3, 4, 5, 6, 7, 8, 9, 10) on the tempering of steels of similar composition to the one under consideration is of interest in connection with the stability of austenite. It has been shown that, when a quenched steel contains a mixture of austenite and martensite, on tempering the martensite breaks down at a lower temperature than the austenite. In particular, Rawdon and Epstein ⁽⁹⁾ say that in a quenched 1.12 per cent. carbon steel the austenite is not decomposed by tempering for 4½ hr. at 200° C. (392° F.), but rapidly decomposes at 250° C. (482° F.), and Whiteley, ⁽¹⁰⁾ referring to a quenched 2.35 per cent. carbon steel, states that the austenite is stable at 200° C. (392° F.), but tempers at 280° C. (536° F.).

Salt at 205° C. (400° F.), 177° C. (350° F.), and 149° C. (300° F.). (Fig. 2).—Cooling from these temperatures showed by the amount

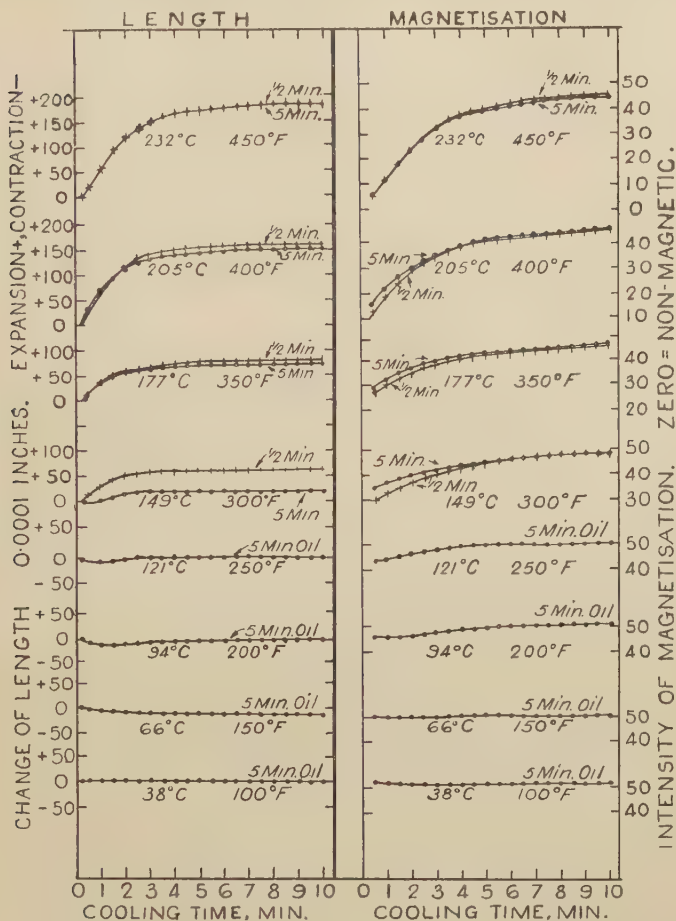


FIG. 2.—Curves showing Changes of Length and Magnetisation on Air-Cooling after Quenching in Salt for $\frac{1}{2}$ min. or 5 min. at the Temperatures shown. Curves marked "oil" were quenched in salt for $\frac{1}{2}$ min. at 232° C. (450° F.), then in oil at the temperatures shown, and then cooled in air.

of expansion and the degree of magnetisation that most of the martensitic change had been completed at 149° C. (300° F.).

The small difference between the $\frac{1}{2}$ -min. and 5-min. curves from 205° C. (400° F.) and 177° C. (350° F.) should be noted. The transformation of austenite to martensite was so rapid at these temperatures that practically all the change had taken place during the first $\frac{1}{2}$ min. in the salt. The difference between the $\frac{1}{2}$ -min. and 5-min. curves from 149° C. (300° F.) was greater, showing that at this temperature the velocity of reaction was slower. It is interesting to note that the 5-min. curve showed a certain degree of under-cooling before the martensite reaction restarted. The microstructures are shown in Figs. 8 and 9. It will be noticed that the martensite in Fig. 9 was smaller grained than that in Fig. 8, owing to the more rapid rate at which it had been formed.

Salt at 232° C. (450° F.) for half a minute, then Oil at 121° C. (250° F.), 94° C. (200° F.), 66° C. (150° F.), and 38° C. (100° F.), for 5 min. (Fig. 2).—Changes in length and magnetisation show that the change to martensite was still incomplete at 94° C. (200° F.), and a distinct under-cooling effect was shown before the change restarted. The microstructures are shown in Figs. 10 and 11 (Plates L. and LI.). It is thought that the amount of troostite in the micrographs is not of special significance, but depends upon how effectively the quenching suppressed the Ar_1 point. The cooling curves from 66° C. (150° F.) and 38° C. (100° F.) do not show any evidence of the martensite change. It is thought probable that at these temperatures the under-cooling effect may be such that the change did not start again in the small cooling range of temperature available. Preliminary experiments in which the cooling was continued to -60° C. (-76° F.) were inconclusive owing to experimental difficulties. However, there is much experimental evidence available showing that a quenched steel of this composition contains austenite at room temperature which may be converted, at least in part, to martensite by cooling in liquid air.^(3, 11, 12, 13, 14, 15)

Salt at 260° C. (500° F.), 288° C. (550° F.), and 316° C. (600° F.). (Fig. 3).—The austenite which was quite stable over a period of 5 min. at 232° C. (450° F.) lost stability as the quenching temperature was raised to 316° C. (600° F.). Even so the decomposition was slow, and after $\frac{1}{2}$ min. in the quenching bath the steel was mainly austenitic, as is shown by the large expansion and

increase in magnetisation on cooling. After 5 min., however, comparatively little austenite remained, particularly at the higher

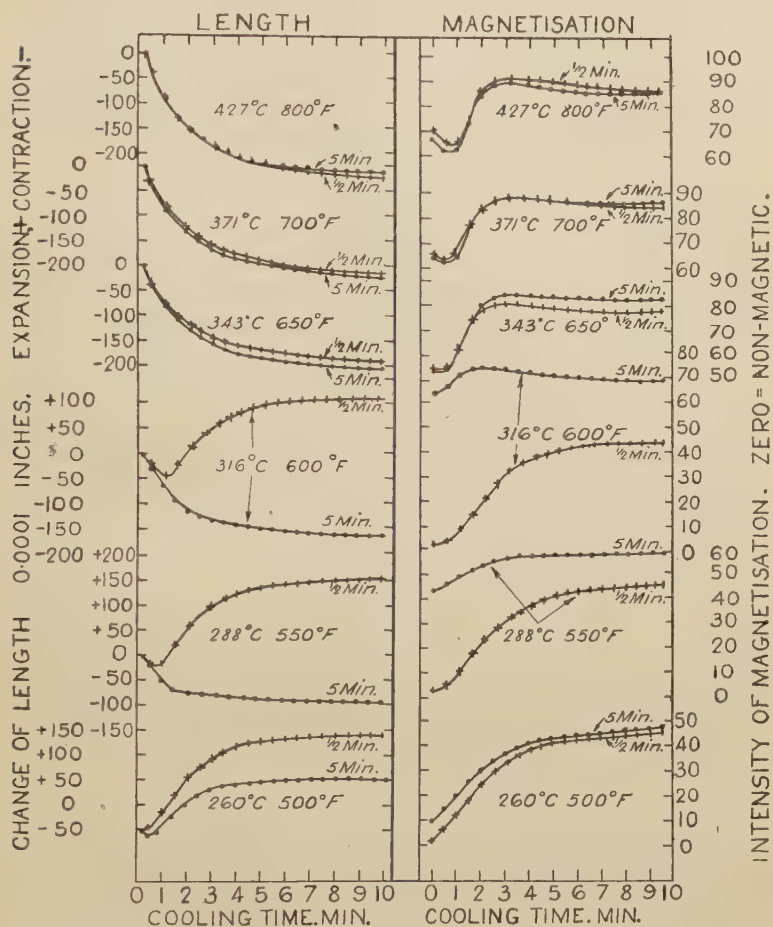


FIG. 3.—Curves showing Changes of Length and Magnetisation on Air-Cooling after Quenching in Salt for $\frac{1}{2}$ min. or 5 min. at the Temperatures shown.

temperatures. The structural nature of the product of decomposition of the austenite is shown in Figs. 12 to 16 (Plates LI. and LII.). It was expected that the decomposition would produce troostite, and the martensitic appearance of the

microstructures was surprising. Apparently the austenite decomposed into a needle-like crystallisation at temperatures above 232°C. (450°F.), as well as below this temperature. Above this temperature, however, the decomposition was slow, and resulted in large needles and low hardness, while below this temperature the decomposition was very rapid, producing smaller needles and great hardness. The phenomenon might well be one of metastable and labile crystallisation, as suggested by Hallimond.⁽¹⁶⁾

Salt at 343°C. (650°F.), 371°C. (700°F.), and 427°C. (800°F.). (Fig. 3).—An increase in the temperature of the quenching medium from 316°C. (600°F.) to 343°C. (650°F.) caused a sudden change in the reaction which took place. The dilatation curves showed little difference between the $\frac{1}{2}$ -min. and 5-min. curves, so that the reaction was extremely rapid and the contraction was continuous, with no evidence of a martensitic expansion. The magnetisation curves showed for the first time a marked increase of intensity of magnetisation at the cementite point A_0 , proving the formation of large amounts of cementite before air-cooling started. The microstructure (Fig. 17) was entirely sorbitic, and showed no needle-like characteristics. It is thought that the marked change in properties and structure was due to the inability of the quenching medium at these temperatures to suppress the A_{r1} change, so that little or no austenite was retained in the steel when it reached the temperature of the salt bath. Otherwise it is difficult to explain the sudden increase in the rate of decomposition of the austenite, and the different type of structure resulting from that decomposition.

Effect of Soaking Time.—In order to determine whether the short soaking time had a material effect on the results, a treatment in salt at 205°C. (400°F.) for 5 min. was repeated with a soaking time of 15 min. instead of 4 min. The increased soaking time had little effect upon the results, as is shown by the following figures: The expansions were 0.0152 in. and 0.0141 in., and the intensities of magnetisation gave 15 and 14 mm. initial deflections, and 46 and 46 mm. final deflections, for the 4-min. and 15-min. soaking times respectively.

The change to martensite was partially complete at 205°C. (400°F.) (see Fig. 2), and the fact that it did not progress further in 5 min. than in $\frac{1}{2}$ min. suggested that the change was

one taking place over a temperature range for a reason not due to sluggishness of the reaction. It was thought that the reason might be non-uniformity in the composition of the austenite. However, a threefold increase in the soaking time did not cause the reaction to proceed any further, and therefore it seems probable that the reason for the temperature range is one of

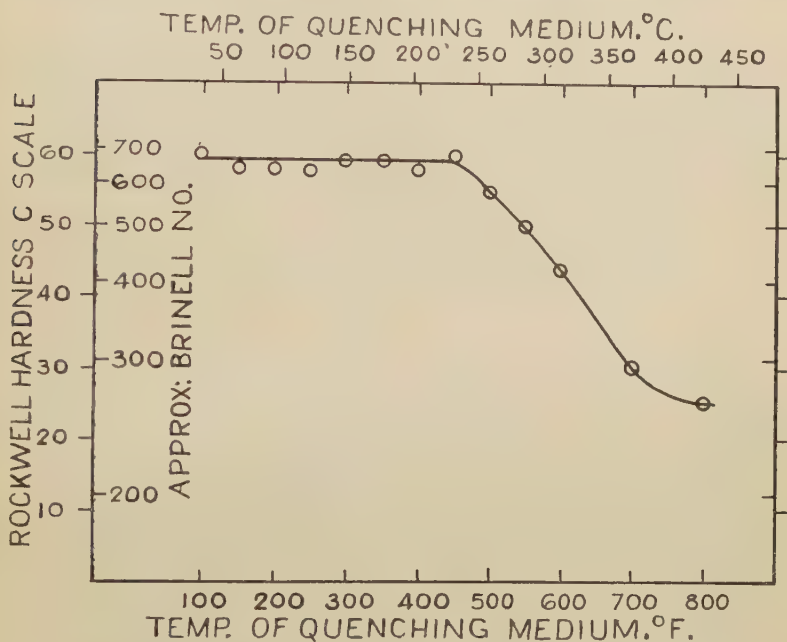


FIG. 4.—Hardness after Quenching in Medium at Temperatures shown for 5 min. and Cooling in Air to Atmospheric Temperature.

fundamental importance in understanding the mechanism of the formation of martensite.

Hardness.—The Rockwell C scale hardness of the specimens at room temperature after various treatments is given in Fig. 4. The hardness is plotted against the temperature of the quenching medium, and a scale showing the approximate Brinell number has been added. The plotted curve refers to the treatments with 5 min. in the quenching medium. It will be seen that the decomposition of austenite below 232° C. (450° F.) resulted in great hardness (Rockwell hardness, C-59; Brinell hardness, 650)

and that as great a hardness resulted from air-cooling as from oil-cooling through the martensitic transformation. On the other hand, when the austenite decomposed above 232° C. (450° F.), the hardness became progressively less, until at 427° C. (800° F.) the Rockwell hardness was C-25 (Brinell hardness about 260).

CONCLUSIONS.

1. A 0·8 per cent. carbon steel may be quenched in a molten salt bath at 232° C. (450° F.) to comparatively stable austenite, which will convert to martensite on cooling. The cooling may be slow or rapid, with practically no influence on the final hardness (Rockwell hardness, C-59 ; Brinell hardness, 650).

2. A two-stage hardening of the type described above should have many commercial applications in the hardening of steel of this class, because the quenching can be placed under full scientific control. The rate at which the change to martensite takes place may be made very slow, and in cases where the steel is drawn without cooling to room temperature the quantity of martensite formed may be controlled. Such treatment should be of value in avoiding quenching cracks and distortion.

3. The fact that the austenitic state is stable in this steel at 232° C. (450° F.) for at least 5 min. opens up the possibility of conducting forming operations at this temperature. The parts would then harden on cooling in air.

4. When the austenite in a 0·8 per cent. carbon steel decomposes below 232° C. (450° F.) the reaction is rapid and the product hard martensite. Above this temperature (at any rate up to 316° C. (600° F.)) the decomposition is comparatively slow (that is, incomplete in 5 min.), and the product has a martensitic appearance. However, the needles are very large, and the hardness is low. It is probable that below 232° C. (450° F.) crystallisation takes place from a labile state, whereas above this temperature the crystallisation is from a metastable state.

5. A comprehensive theory of the formation of martensite has not been attempted in this paper because of the limited facts available, but it is thought that further experiments, using the methods described, should help considerably towards a better understanding of the hardening of steel.

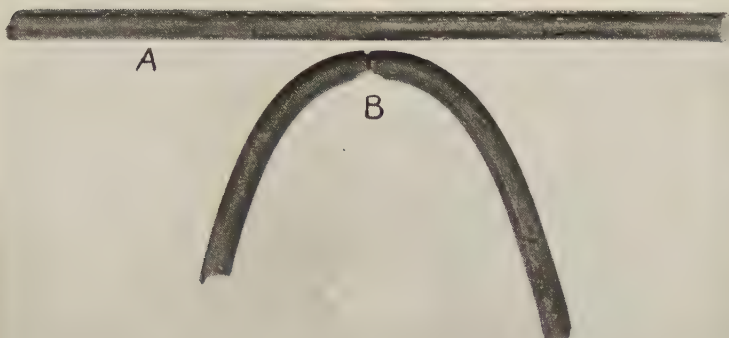


FIG. 5.—A straight wire (*A*) was quenched in salt at 232° C. (450° F.), removed, immediately bent (*B*), and then allowed to cool in air. When cold, another attempt to bend caused the quite brittle fracture shown.

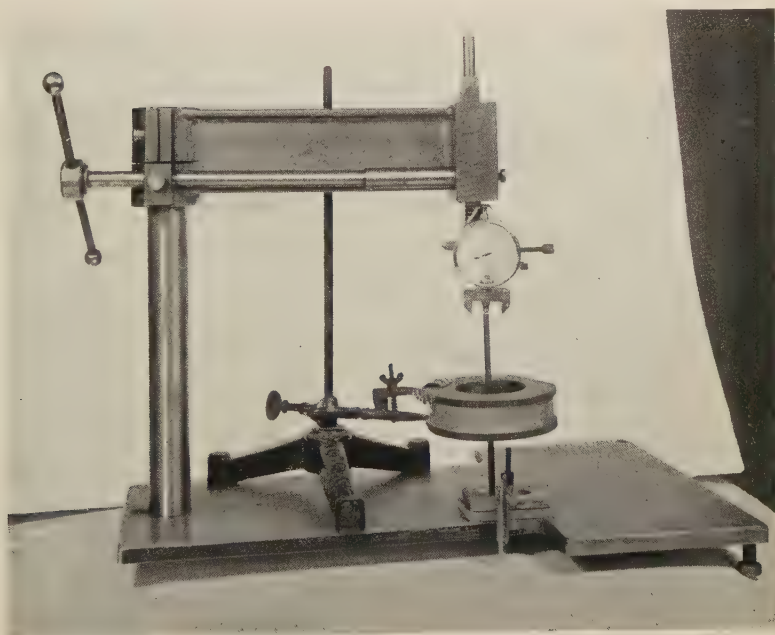


FIG. 6.—Dilatometer and magnetising coil.



FIG. 7.—Specimen quenched in salt at 232° C. (450° F.) for 5 min., then cooled in air.

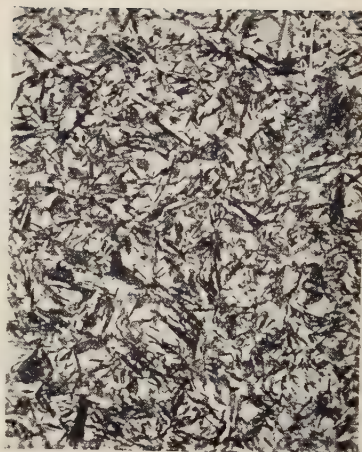


FIG. 8.—Specimen quenched in salt at 205° C. (400° F.) for 5 min., then cooled in air.



FIG. 9.—Specimen quenched in salt at 149° C. (300° F.) for 5 min., then cooled in air.



FIG. 10.—Specimen quenched in salt at 232° C. (450° F.) for $\frac{1}{2}$ min., then in oil at 94° C. (200° F.) for 5 min., then cooled in air.

Magnification 1000 diam. ; reduced in reproduction to one-half.



FIG. 11.—Specimen quenched in salt at 232° C. (450° F.) for $\frac{1}{2}$ min., then in oil at 38° C. (100° F.) for 5 min., then cooled in air.



FIG. 12.—Specimen quenched in salt at 260° C. (500° F.) for 5 min., then cooled in air.



FIG. 13.—Specimen quenched in salt at 288° C. (550° F.) for $\frac{1}{2}$ min., then cooled in air.



FIG. 14.—Specimen quenched in salt at 288° C. (550° F.) for 5 min., then cooled in air.

Magnification 1000 diam. ; reduced in reproduction to one-half.



FIG. 15.—Specimen quenched in salt at 316° C. (600° F.) for $\frac{1}{2}$ min., then cooled in air.



FIG. 16.—Specimen quenched in salt at 316° C. (600° F.) for 5 min., then cooled in air.



FIG. 17.—Specimen quenched in salt at 343° C. (650° F.) for $\frac{1}{2}$ min., then cooled in air.

Magnification 1000 diam. ; reduced in reproduction to one-half.

The publication of this paper would not have been possible but for the generous help and interest of many members of the Research Department of the American Chain Co. In particular, the author is indebted to Mr. A. V. de Forest for his help in designing and constructing the magnetic and dilatation equipment, and for his great interest in the progress of the work; to Messrs. H. H. Passolt and L. D. Edwards for the photomicrography; and to Mr. K. Pitschner for the chemical analyses. No less is he indebted to Mr. C. A. McCune, Research Director, for his encouragement, and to the Directors of the American Chain Co., Bridgeport, Connecticut, for their generous permission to publish the paper.

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DISCUSSION.

Professor J. H. ANDREW (Glasgow) remarked that Mr. Lewis' paper showed very clearly that there was a definite change from austenite to martensite at a temperature of about 200° C. He complimented the author on his neat method of attacking the problem.

Mr. J. H. WHITELEY (Consett) said he thought Mr. Lewis had given an extremely interesting paper. To demonstrate that, even in a 0.8 per cent. carbon steel, austenite was comparatively stable at 230° C. was certainly of importance. The lattice structure shown in Figs. 12, 14, and 16 appeared to be identical with that which could be obtained by tempering martensite containing from 0.75 to 1.5 per cent. of carbon at 200° C. The change which then occurred was remarkable and extraordinarily rapid. There was no resemblance between the original martensite structure and that produced. In a recent paper on martensite and troostite he had given some evidence which indicated that a part of the martensite was actually converted again into austenite by the treatment, while the remainder changed into troostite. The austenite in the lattice structure then appeared white on etching. He was aware that no one believed that to be the case, yet, nevertheless, it was not impossible. In a composite sample with a carbon content ranging from 0.2 to 2.3 per cent., he had found the lattice structure obtained by tempering to merge gradually into that of austenite and zigzag troostite as the carbon increased to above 1.5 per cent. Throughout, the white constituent appeared identical, and it was certainly austenite in the high-carbon region. Was the stability of austenite greater between 200° and 250° C. than at higher temperatures up to A_r'' where martensite had hitherto been considered to form? It would be valuable if Mr. Lewis could investigate that point by his method.

Mr. DARTREY LEWIS, in reply, said the discussion had been confined mainly to the scientific aspect of his paper. He was very grateful to the two gentlemen who discussed the paper, and he took it from their remarks that they agreed with him fairly well. Mr. Whiteley's suggestion that under certain conditions the change from austenite to martensite was reversible was extremely interesting.

He had been rather disappointed, however, that no discussion took place on the practical aspect of the paper, and he would like to say again that it had two possible applications. One arose from the fact that if one quenched a 0.8 per cent. carbon steel in a quenching medium at about 230° C. it was austenitic and soft, and remained austenitic for at least 5 min., which gave time for it to be formed, if so desired. Coil springs, for instance, could be made by quenching the

spring wire in a continuous operation in a salt bath at $230^{\circ}\text{C}.$, then letting it run out of the salt bath as austenite and wrapping it up in the coiling machine as a coil which, as it cooled down to room temperature, would harden up to 650 Brinell hardness. Thus one would obtain a heat-treated spring in a new way, without the disadvantages of having to form the coil first and then heat it up to the quenching temperature, which caused a lot of oxidation and deformation. The suggested method was well worth trying. The other application was based on the fact that when the steel was quenched in a salt bath at that temperature it would harden on cooling in air. In that way quenching cracks and distortion would be avoided, because the rate at which the steel went through the transformation was very slow; apparently it might be as slow as one liked.

Another point was that the steel need not be cooled all the way through the transformation; it could be cooled so as to have definitely some austenite still left, and then tempered immediately, so that some austenite never went over to martensite. That would reduce the strains in the material, because there would be some soft matrix material there all the time.

CORRESPONDENCE.

Dr. M. S. FISHER and Dr. J. M. ROBERTSON (London) wrote: Mr. Lewis has shown that when austenite is rapidly cooled by immersing it in molten salt, the rate of decomposition of the austenite at the temperature of the cooling medium decreases progressively as the temperature of the medium is lowered from $343^{\circ}\text{C}.$ to $232^{\circ}\text{C}.$ If the steel is removed from the salt bath before all the austenite has decomposed and is allowed to cool in air, the remaining austenite decomposes rapidly, with an accompanying expansion, as the temperature falls. When the temperature of the medium is below $232^{\circ}\text{C}.$, and the steel is withdrawn from the bath after a given time interval, the amount of expansion that occurs during the air-cooling decreases as the temperature of the medium is lowered; this, however, is not because of an increase in the rate of decomposition of austenite at the temperature of the medium, but because the austenite decomposes while cooling to the temperature of the medium. Similar results, which illustrate the phenomena under discussion even more clearly, were obtained by Matsushita,¹ who cooled specimens in water to temperatures in the Ar'' range, withdrew them from the water and held them in air for varying times, and finally cooled them to the ordinary temperature in water. He found that the decomposition of the austenite at Ar'' proceeded rapidly while the specimen was cooling in water, that it practically stopped when the specimen was held in air, and that it again proceeded rapidly when the specimen was replaced in

¹ *Science Reports of the Tôhoku Imperial University, Sendai*, 1923, vol. xii. p. 7.

the water. He further found that if the final cooling was performed in oil instead of water, the time required to complete the change was proportional to the rate of cooling.

These results, together with those obtained by Tammann and Scheil¹ and by Andrew, Fisher, and Robertson,² show that the decomposition of austenite at constant temperature is a function of time, whereas during continuous cooling it is a function of the rate of cooling. The lower the temperature, the more slowly does austenite decompose at constant temperature. The reason is that at constant temperature austenite decomposes into an aggregate of α -iron and cementite; the rate of the reaction is controlled by the rate of formation of cementite, which, being dependent on the rate of diffusion of carbon, decreases as the temperature is lowered. Decomposition of austenite during continuous cooling proceeds as the temperature falls, and at a rate proportional to the rate at which the temperature falls. The reason is that the austenite changes directly to supersaturated α solid solution (commonly called martensite). As the carbon remains in solution, the rate of the reaction is independent of the rate of formation of cementite; it is of course affected by the rate of diffusion of carbon, but only to a comparatively small extent, because the amount of carbon that must diffuse is comparatively small.

From the fact that continuous formation of supersaturated α solid solution takes place only during continuous cooling, it may be deduced that the reaction involves selective freezing. The austenite does not change suddenly into α -iron with the carbon trapped *in situ*, but a proportion of the carbon is rejected by the α solution, and diffuses into the mother austenite. The amount of carbon transferred from the α solution to the austenite may be very small, but some transference of carbon must take place, for otherwise continuous formation of supersaturated α solution could proceed at constant temperature. Actually, the formation of the first minute quantity of α solution increases the carbon concentration of the austenite in its immediate vicinity. This effectively stops more α solid solution from forming round the original centres. The reaction can only continue if the temperature is lowered; crystallisation can then continue round the original centres and at new centres, the concentration of both the austenite and the α solid solution increasing as the temperature falls. The formation of supersaturated α solid solution at A_r'' is therefore a process similar to the formation of ferrite under normal conditions; it involves selective freezing, it proceeds continuously as the temperature falls, and it stops when the temperature remains constant.

Mr. LEWIS wrote, in reply to Dr. M. S. Fisher and Dr. J. M. Robertson, that he was very interested in their views regarding their theory of the manner of decomposition of austenite. He had given considerable

¹ *Zeitschrift für anorganische Chemie*, 1926, vol. cxxvii. p. 1.

² *Proceedings of the Royal Society*, 1926, (A), vol. cx. p. 391.

thought to the theoretical aspect of the phenomena described in his paper, but did not feel ready at the time that the paper was presented to put forward his ideas on the subject. He was in general agreement with the views expressed by Dr. Fisher and Dr. Robertson, except that he was not sure that the decomposition of austenite at a constant temperature was governed by the precipitation of cementite in the temperature range under consideration. As a result of further experiments similar to those described in his paper, he hoped to be able to put forward a more satisfying theory of the decomposition of austenite than was at present available.

CONSTITUTIONAL DIAGRAMS FOR CAST IRONS AND QUENCHED STEELS.*

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(1) *Introduction*.—While making a number of crucible melts of grey cast irons of various total carbon and silicon contents, from mixtures of Swedish white iron, Armco iron, ferro-silicon, ferro-manganese, and ferro-phosphorus, it was found that in many cases irons having identical chemical compositions, cast under identical conditions (but melted under different conditions), had widely different microstructures, combined carbon contents, tendencies to chill, and mechanical properties.

Typical microstructures of medium silicon grey irons of similar chemical compositions but different microstructures are shown in Figs. 16 and 17 (Plate LIII.), while similar micrographs for high-silicon irons are shown in Figs. 18 and 19. It will be seen that in one type of iron the graphite is in a very finely divided form, which has been called "supercooled graphite," whereas in the other type of iron the graphite is in the form of relatively coarse flakes, which has been termed "normal graphite." (All intermediate sizes have also been obtained.) It has also invariably been found that the fine graphite tends to be associated with ferrite in the matrix, while the coarse graphite tends to be associated with pearlite in the matrix—for silicon contents below about 3 per cent. Fine (supercooled) graphite structures similar to the above have been obtained by Piwowarsky,⁽¹⁾ Hanemann,⁽²⁾ Bardenheuer and Zeyen,⁽³⁾ and others by superheating the melt. The explanation advanced by these investigators is that the refining of the graphite is due to the destruction of graphite nuclei in the melt. Schütz⁽⁴⁾ has obtained similar structures by casting high-silicon (3·5 per cent. silicon) irons in chill moulds. Irresberger⁽⁵⁾ has obtained them by jolting molten cast iron which had been melted with steel additions. This fine graphite structure had

* Received February 16, 1929.

also been obtained—as shown by their micrographs—by earlier investigators—for instance, Hague and Turner,⁽⁶⁾ Coe,⁽⁷⁾ &c.

By controlling the melting conditions in the above-mentioned crucible melts it was possible to make two types of grey iron, which have been grouped as series A and series B respectively. In series A the graphite was largely of the fine (supercooled) type, although a certain amount of coarser graphite was also present in certain cases. In series B, on the other hand, the graphite was almost entirely of the coarse (normal) type.

The combined carbon contents of 1·2-in. diam. sand-cast bars of series A and series B irons are shown in Fig. 1, plotted against total carbon contents vertically and silicon contents horizontally. The manganese contents were 1 per cent. in all cases, except where a full circle has been drawn round a combined carbon content, which indicates a manganese content of 0·3 per cent., or a dotted circle which indicates a manganese content of 0·6 per cent. The phosphorus contents were 0·03 per cent. in all cases, except where a line has been drawn beneath the number, which indicates a phosphorus content of 0·3 per cent. The sulphur contents were 0·03 per cent. in all cases.

Curved chill lines have been drawn, which separate grey iron bars from the white and mottled iron bars. Lines showing the effect of silicon on the carbon content of the eutectic have also been included, also dotted curves dividing pearlitic-ferritic irons from ferritic irons in series A and pearlitic irons from ferritic irons in series B. It will be noted that the combined carbon contents of irons in series A are lower than those of irons of similar chemical composition in series B, which is in agreement with the microstructures referred to above.

Chill curves—that is to say, curves dividing white and mottled irons from grey irons—for 1·2-in., 0·875-in., 0·6-in., and 0·4-in. diam. sand-cast bars are shown in Fig. 2. It will be seen that the irons in series A of the supercooled (fine) graphite type show a considerably greater tendency to chill than irons in series B of the normal (coarse) graphite type. It is noteworthy that irons in series A show an increased tendency to chill, but have lower combined carbon contents on solidifying grey. The fractures of the grey iron bars were also markedly different.

In series A the fractures tended to be very finely granular,

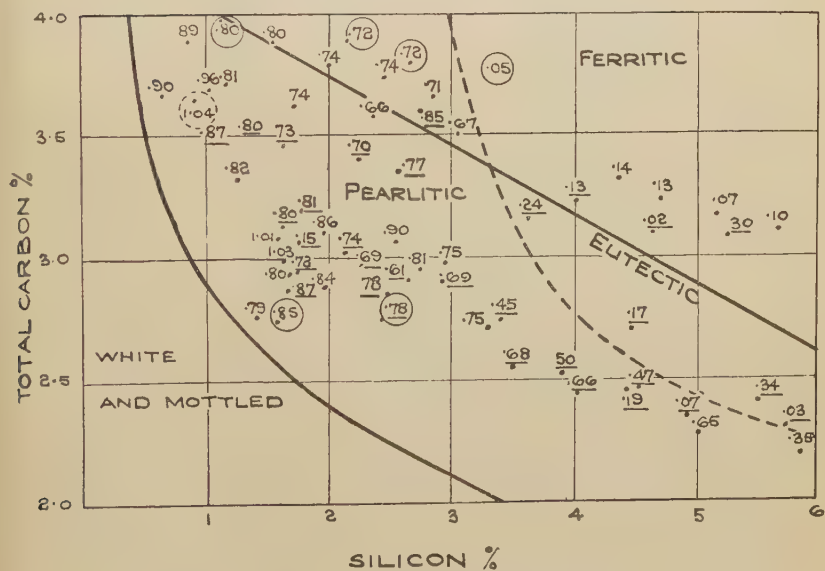
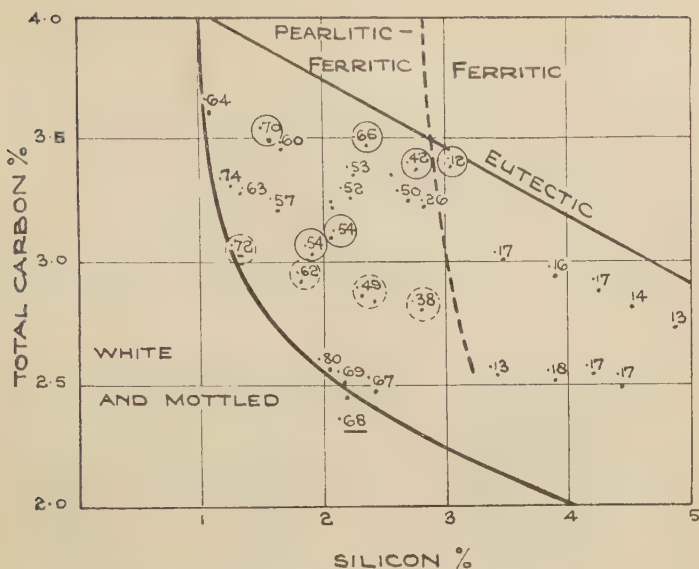
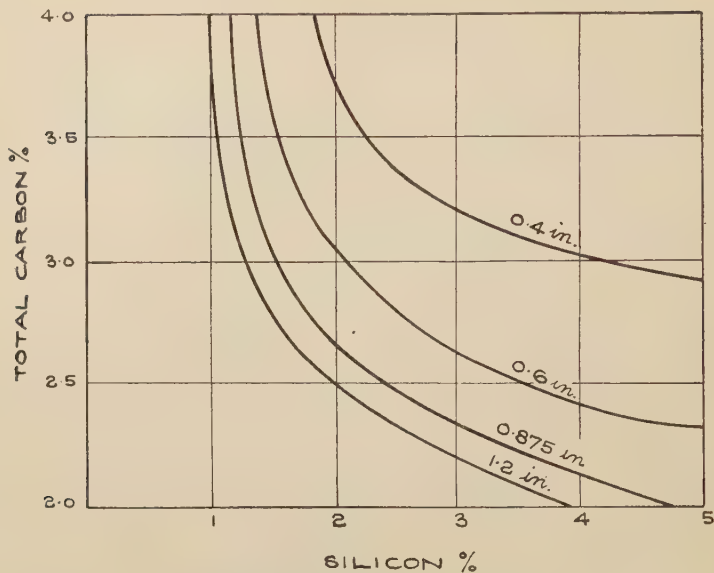
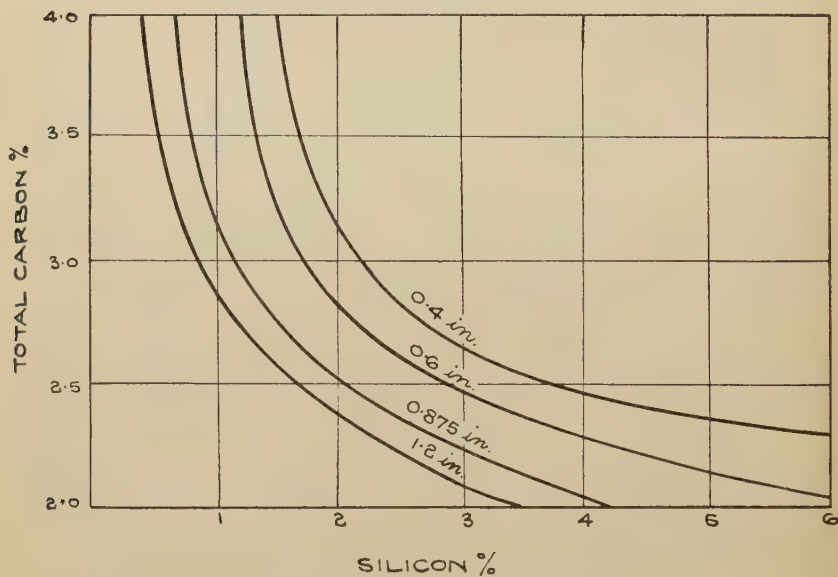


FIG. 1.—Combined Carbon Contents of 1.2-in. diam. Sand-Cast Bars.



Series A—Supercooled fine graphite.



Series B—Normal coarse graphite.

FIG. 2.—Chill Lines dividing Grey Irons from White and Mottled Irons for 1.2, 0.875, 0.6, and 0.4 in. diam. Sand-Cast Bars, plotted against total carbon and silicon contents.

and dull black or sooty in appearance. A typical fracture of a 0·875-in. diam. sand-cast bar in series A containing total carbon 2·81, combined carbon 0·14, silicon 4·53, manganese 0·98, sulphur 0·03, and phosphorus 0·03 per cent., is shown in Fig. 20 (Plate LIV.). In series B, on the other hand, the fractures tended to be coarsely granular, to be steely-grey rather than dull black, and to contain numerous shining graphite flakes. A typical fracture is shown in Fig. 21 of an iron in series B containing total carbon 2·71, combined carbon 0·17, silicon 4·46, manganese 1·10, sulphur 0·03, and phosphorus 0·30 per cent.—



FIG. 3.—Mottled Fracture, typical of Irons in Series A (supercooled fine graphite type). Natural size.

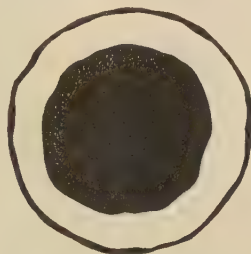


FIG. 4.—Mottled Fracture, typical of Irons in Series B (normal coarse graphite type). Natural size.

that is, of similar composition to that shown in Fig. 20. (Figs. 20 and 21 were photographed on the same plate.) The fractures are, of course, also largely dependent on the total carbon and silicon contents.

The fractures of the mottled bars were also different in irons in series A and B, as shown in Figs. 3 and 4. In Fig. 3 the white fracture contains spots of supercooled graphite throughout, and a ring of supercooled graphite round the edge. Bardenheuer and Zeyen⁽³⁾ (*loc. cit.*, p. 362) have suggested that such graphite is formed by the sand particles of the mould acting as nuclei. It seems likely, however, that its formation is also due to the fact that the outer layers are able to undergo more readily the expansion necessary for graphitisation. Except in the graphitised spots, the inside layers have been prevented from solidifying grey with consequent expansion, owing to the resistance

and pressure exerted by the contraction of the solidified outer layers. The form of this graphitisation is reminiscent of troostite in martensite. The fractures of mottled bars of series B type shown in Fig. 4 were normal—namely, white on the outside and grey in the centre, consequent on the retardation of the rate of cooling from the edge to the centre.

The internal pressure consequent on supercooling followed by the expansion due to an iron of series A type solidifying grey is

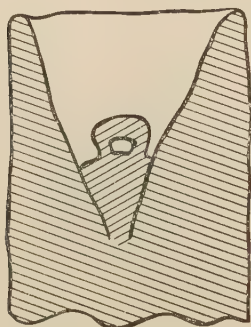


FIG. 5.—Pipe, typical of Irons in Series A (supercooled fine graphite type), showing extruded eutectic. Natural size.

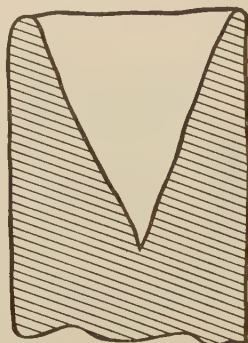


FIG. 6.—Pipe, typical of Irons in Series B (normal coarse graphite type). Natural size.

indicated by the nature of the pipe shown in Fig. 5. In such a case the expansion accompanying the deposition of graphite from the melt has caused the eutectic, which was still liquid between solid austenite dendrites in the central portion of the hypoeutectic test-bar, to be squeezed so that it has been extruded and formed globules in the pipe. (Microscopic examination showed that such globules were of eutectic composition.) If the conditions are suitable, the pressure may be sufficient to prevent the central portion solidifying grey—in which case internal chill will again result. The pipes in the series B type of iron (as shown in Fig. 6) were normal—that is, they contained no extruded globules.

The phosphide network structures at a magnification of

25 diam. obtained by deep etching in nitric acid (sp. gr. 1.2) were larger in the grey irons in series A than in the grey irons in series B. Typical networks of irons in series A and B are shown respectively in Figs. 22 and 23 (Plate LIV.). These networks are presumably due to the crystallisation of the liquid eutectic (contained between the solid austenite dendrites) proceeding from a limited number of centres. From each centre the crystallisation proceeds outwards until it meets crystallisation proceeding from a neighbouring centre. The last portions of eutectic to solidify (the phosphide eutectic) consequently crystallise farthest away from the centres and give the network structure. The fact that the network size is larger in series A than in series B may be due to the slower rate of solidification consequent on supercooling.

In order to explain the above results and certain others which will be referred to in due course, constitutional diagrams for cast irons have been constructed in which normal and supercooled systems are shown.

(2) *Analogy with Aluminium-Silicon Alloys.*—A similar type of equilibrium diagram showing normal and supercooled systems* has recently been proposed for the aluminium-silicon alloy system by Gwyer and Phillips,⁽⁸⁾ Gayler,⁽⁹⁾ and others. The microstructures of modified (supercooled) and normal aluminium-silicon alloys (shown in their papers) are strikingly similar to those shown in Figs. 16 to 19.

The modified aluminium-silicon alloys are obtained by chilling, or by adding metallic sodium or caustic soda or certain other modifiers to the melt. The precise action of these modifiers is not completely understood, but, from analogy with cast iron, it may consist in fluxing and removing from the melt particles—such as oxides—which act as nuclei. It is suggested that the fine and coarse graphite structures obtained in grey cast irons are analogous to the fine and coarse structures obtained in modified and normal aluminium-silicon alloys. Constitutional diagrams have consequently been constructed for cast iron showing normal

* Diagrams showing normal and supercooled systems were first proposed by Miers and his collaborators to represent the crystallisation of various substances from aqueous and organic solutions. The principles of supercooling, &c., enunciated have also been applied to alloy systems by Huntington and Desch, Stead, Portevin, Hallimond, and others. (See Miers⁽¹⁴⁾ and Hallimond.⁽¹⁵⁾)

and supercooled systems, both for the austenite-graphite system and for the austenite-cementite system. In view of the con-

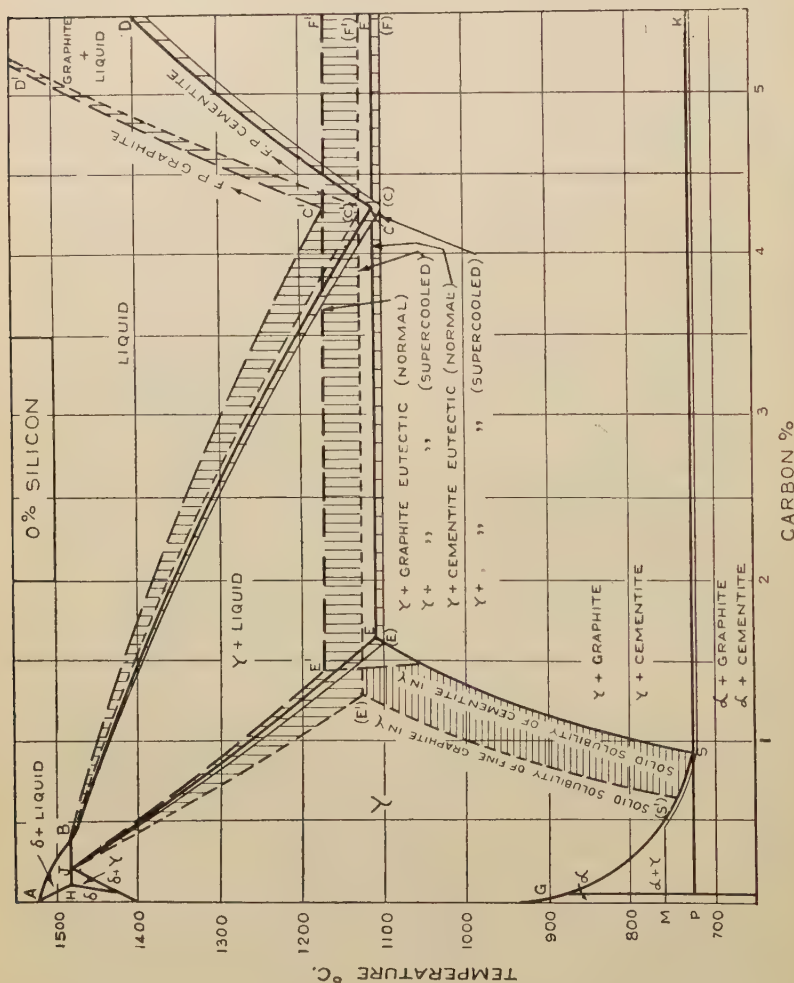


Fig. 7.—Constitutional Diagram for Cast Irons containing no Silicon.

siderable effect of silicon on the positions of the phase boundaries, three iron-carbon diagrams have been constructed, one for 0 per cent. of silicon, one for 2 per cent. of silicon, and one for 4 per cent. of silicon, as shown in Figs. 7, 8, and 9.

(3) *Positions of Phase Boundaries in Iron-Carbon-Silicon Diagrams.*—The temperatures and compositions assigned to the

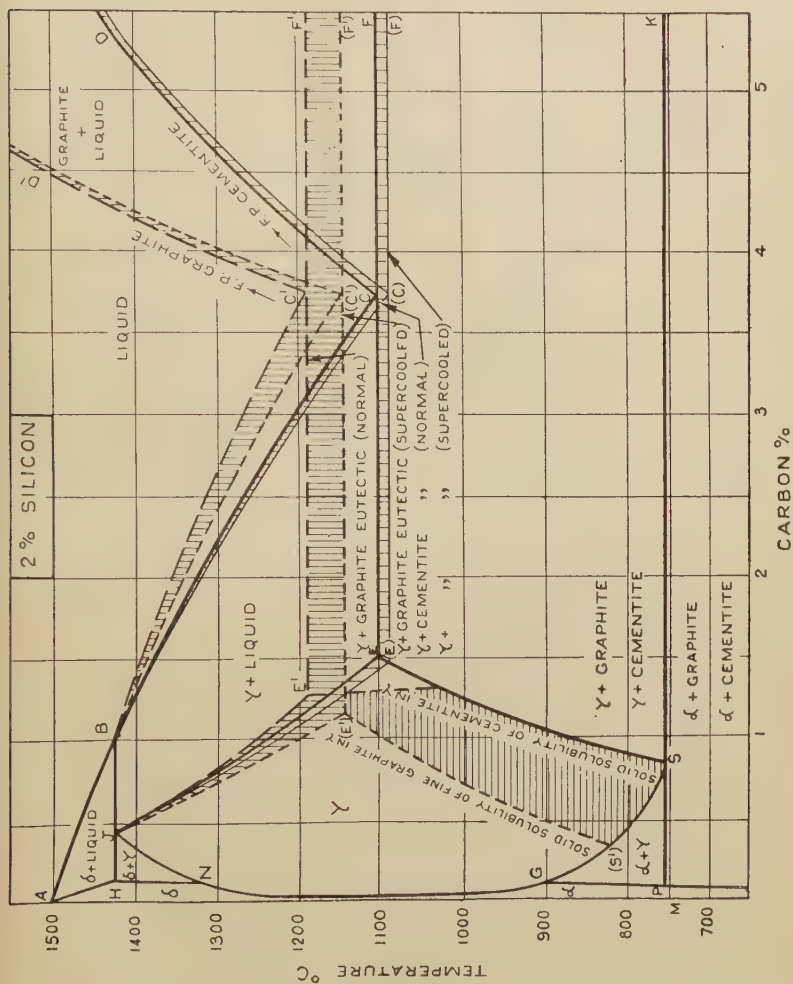


Fig. 8.—Constitutional Diagram for Cast Irons containing 2 per cent. of Silicon.

approximately correct, and experiments are being carried out with the object of ascertaining them more accurately.

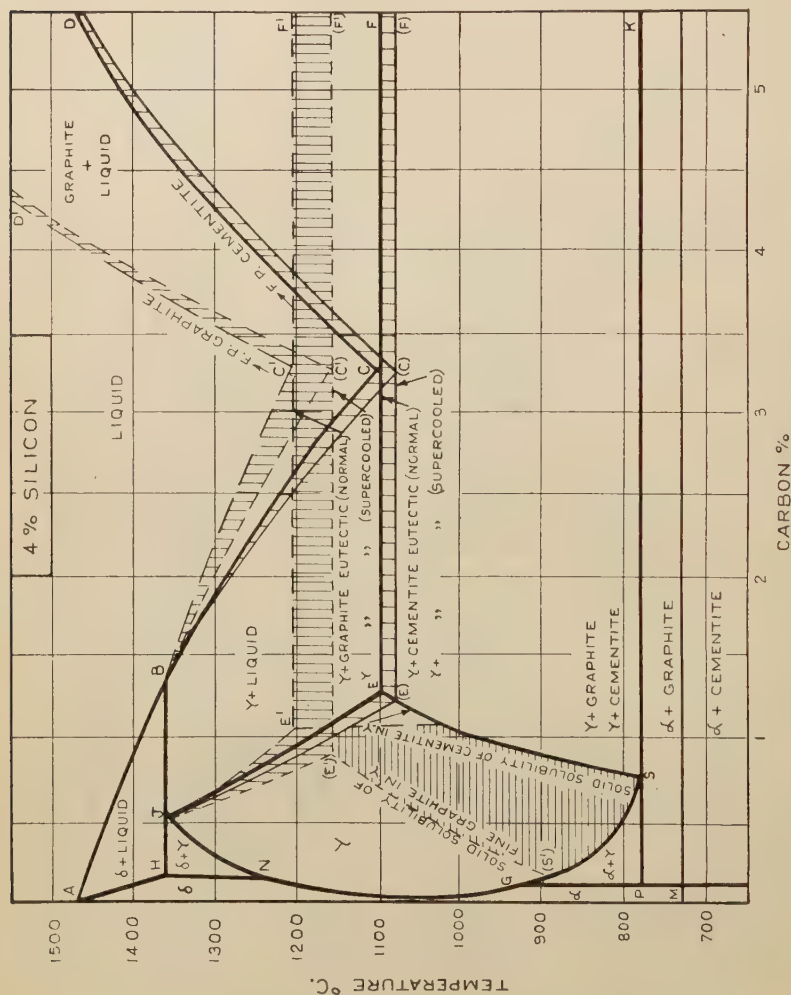


FIG. 9.—Constitutional Diagram for Cast Irons containing 4 per cent. of Silicon.

(4) *Normal and Supercooled Austenite-Graphite and Austenite-Cementite Eutectic Temperatures.*—The temperatures assigned to the fine graphite and coarse graphite eutectics, respectively, in Figs. 7, 8, and 9, have been arrived at from a consideration of

the results of Wüst and Petersen⁽¹⁰⁾ and Hague and Turner,⁽⁶⁾ plotted in Fig. 10. It will be seen that the eutectic temperatures found by Wüst and Petersen are some 20° higher than those found by Hague and Turner. Wüst and Petersen had excess carbon present in their melts, and it is suggested that this excess carbon provided the nuclei which prevented supercooling and caused the melts to solidify according to the coarse graphite eutectic. This is also evident from their micrographs.

Micrographs published by Hague and Turner show, on the

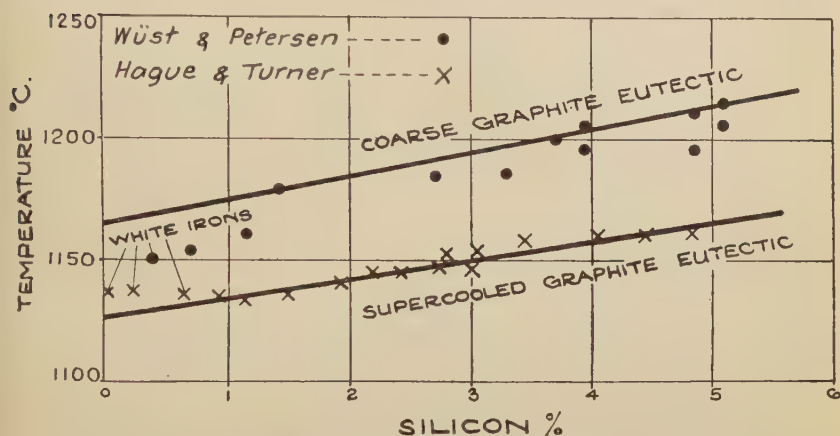


FIG. 10.—Effect of Silicon on the Austenite-Graphite Eutectic Temperature.

other hand, supercooled graphite eutectic structures in all cases. It consequently seems probable that the lower eutectic temperatures found by them are representative of the supercooled eutectic. (The results of other investigators—namely, Gontermann,⁽¹¹⁾ Hanson,⁽¹²⁾ and Honda and Murakami⁽¹³⁾—are in most cases intermediate.) The temperatures assigned to the coarse eutectics in Figs. 7, 8, and 9 have consequently been taken from the data of Wüst and Petersen, while the temperatures for the fine graphite eutectics have been taken from the data of Hague and Turner.

Normal and supercooled eutectic lines for white irons have also been drawn in Figs. 7, 8, and 9. This appears to be probable from a consideration of the microstructures shown in Figs. 24 and 25 (Plate LV.). The irons shown in these figures contained

carbon 3.9 and silicon 0.6 per cent., and were practically identical in chemical composition; they were crucible-melted and sand-cast in the form of 1-in. \times $\frac{1}{2}$ -in. bars under practically identical conditions. Fig. 24 was a Swedish pig iron plus 10 per cent. ferro-silicon mixture, and Fig. 25 was a refined pig iron plus arc carbon mixture. It will be seen, however, that in Fig. 25 the austenite part of the eutectic has coagulated and joined up with the primary austenite dendrites, while in Fig. 24 this has not occurred. It is suggested, therefore, that Fig. 24 represents the supercooled eutectic, and that the microstructure in Fig. 25 indicates that after the austenite dendrites had solidified there were graphite or other nuclei present in the still molten eutectic which caused the precipitation of small amounts of austenite-graphite eutectic, which in turn caused the precipitation of the white iron eutectic at its highest possible temperature, with consequent maximum coalescence.

The γ + cementite normal eutectic has been placed at 1110° C. in Fig. 7, and at 1105° C. and 1100° C. in Figs. 8 and 9, and the supercooled eutectic has been placed 10°, 15°, and 20° lower in each diagram. The temperatures of these eutectics are, however, not known with any degree of certainty, and experiments are being carried out to determine the actual temperatures. The letters representing the supercooled systems in Figs. 7, 8, and 9 have been enclosed in brackets.

(5) *Carbon Contents of Normal and Supercooled Eutectics.*—The point *C'* for the coarse graphite eutectic has been placed at 4.3 per cent. of carbon for 0 per cent. of silicon, 3.75 per cent. of carbon for 2 per cent. of silicon, and 3.25 per cent. of carbon for 4 per cent. of silicon, in accordance with the data of Wüst and Petersen,⁽¹⁰⁾ plotted in Fig. 11. The effect of silicon on the carbon content of the fine graphite eutectic is apparently approximately the same, since the microstructures of alloys containing 3.5 per cent. of silicon and about 3.3 per cent. of carbon showed areas of supercooled graphite of approximately eutectic structure. The effect of silicon on the carbon content of the white iron (austenite-cementite eutectic) also appears to be approximately the same, judging by planimetric measurements on microstructures of white irons containing about 3 per cent. of silicon. The normal and supercooled graphite-austenite and cementite-

austenite eutectic compositions have consequently been placed at the same carbon contents in each of the diagrams.

(6) *Liquidus Lines*.—Liquidus lines have been drawn in, joining the four eutectic points with the point *B* on the low-carbon side of the eutectics, and the freezing points of graphite and cementite, respectively, on the high-carbon side of the eutectics.

(7) *Solid Solubility of Graphite and Cementite in γ -Iron*.—The lines (*S'*)(*E'*), representing the solid solubility of graphite in γ -iron in the 0, 2, and 4 per cent. silicon diagrams have been taken

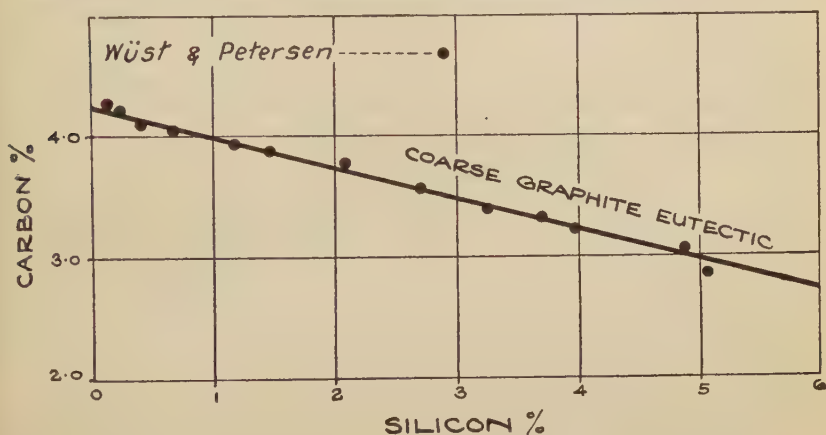


FIG. 11.—Effect of Silicon on the Carbon Content of the Austenite-Graphite Eutectic.

from the work of Morschel.* The positions of the points *E'* in Figs. 7, 8, and 9, obtained by the intersection of these graphite solid solubility lines and the coarse graphite eutectic temperature lines, have been checked by chemical analysis in the following manner. It has been found † that if manganese is only present in traces in cast iron the secondary cementite is stabilised by traces of sulphur and does not decompose into graphite. Coarse graphite irons of this type containing 2 per cent. and 4 per cent. of silicon, respectively, have been found to have combined carbon contents approximating to the values shown for the points *E'* in the diagrams in Figs. 8 and 9. The position of the points

* See Schüz (4) (*loc. cit.*, p. 387).

† Paper read before the Institute of British Foundrymen, June 1929; *Foundry Trade Journal*, 1929, vol. xli. Aug. 1, pp. 79–83.

(E') has been checked in a similar manner with fine graphite alloys. The line SE for the solid solubility of the cementite in γ -iron has been taken from the diagram published by the Verein deutscher Eisenhüttenleute,* and has been moved to the left slightly (that is, to lower solid solubilities) for increasing silicon contents. The position of the point E for high silicon contents is not, however, known with any certainty.

(8) *Eutectoid Carbon Content and Eutectoid Temperature.*—The point S has been placed at 0.9 per cent. of carbon for 0 per cent. of silicon, and its carbon content with 2 per cent. and 4 per cent. of silicon has been estimated in the following manner. Grey irons containing coarse graphite in a uniformly pearlitic matrix have been obtained with silicon contents as high as 4 per cent. and over. With 4 per cent. of silicon the combined carbon content of such irons has been found to be 0.7 per cent. (see Fig. 1), which figure has consequently been taken to represent the carbon content at the point S in Fig. 9. The lines PSK have been placed at 720°C. for 0 per cent. of silicon, 750°C. for 2 per cent. of silicon, and 780°C. for 4 per cent. of silicon. This raising of the eutectoid temperature has been taken from the results of Wüst and Petersen,⁽¹⁰⁾ Hague and Turner,⁽⁶⁾ Gontermann,⁽¹¹⁾ and Hanson,⁽¹²⁾ plotted in Fig. 12. Incidentally, with low carbon contents—that is, below 0.9 per cent.—considerably lower temperatures for this line have been found by Hanson⁽¹²⁾ and others, as shown by the results plotted in Fig. 12, where low carbon contents have been written in against the dots, &c. It is suggested that this is due to supercooling consequent on the absence of carbide nuclei.

(9) δ - γ and γ - α *Allotropic Changes.*—The lines AB and BH have been taken from the work of Ruer and Klesper⁽¹⁶⁾ for 0 per cent. silicon alloys; for 2 per cent. silicon alloys (Fig. 8) they have been taken from the work of Hanson, while for 4 per cent. silicon alloys (Fig. 9) extrapolated values have been estimated from these two investigations. The point N , at which the δ - γ change takes place, has been placed for 0 per cent. of silicon according to the work of Ruer and Klesper,⁽¹⁶⁾ of Wever and Giani,⁽¹⁷⁾ and of Sanfourche,⁽¹⁸⁾ whose results are plotted in Fig. 13. With higher silicon contents the δ - γ change does not occur,

* See Schüz (4) (*loc. cit.*, p. 383).

according to the results of Wever and Giani, which confirmed the prediction of Oberhoffer.⁽¹⁹⁾ These investigators found that the δ - γ change was absent in alloys containing over 1.5 per cent. of silicon; they worked, however, with alloys made from exceedingly pure electrolytic iron. Sanfourche,⁽¹⁸⁾ on the other hand, working with alloys made from Swedish wrought iron containing a few thousandths per cent. of carbon, found the δ - γ change was

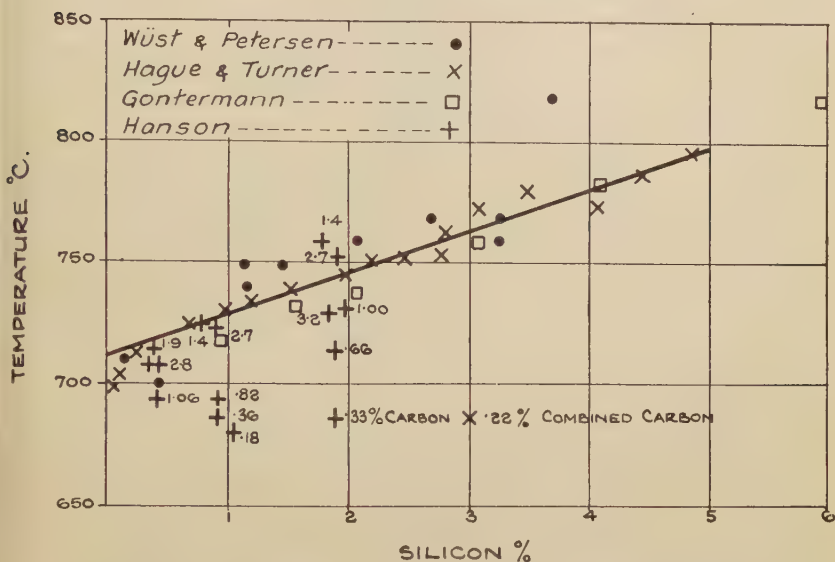
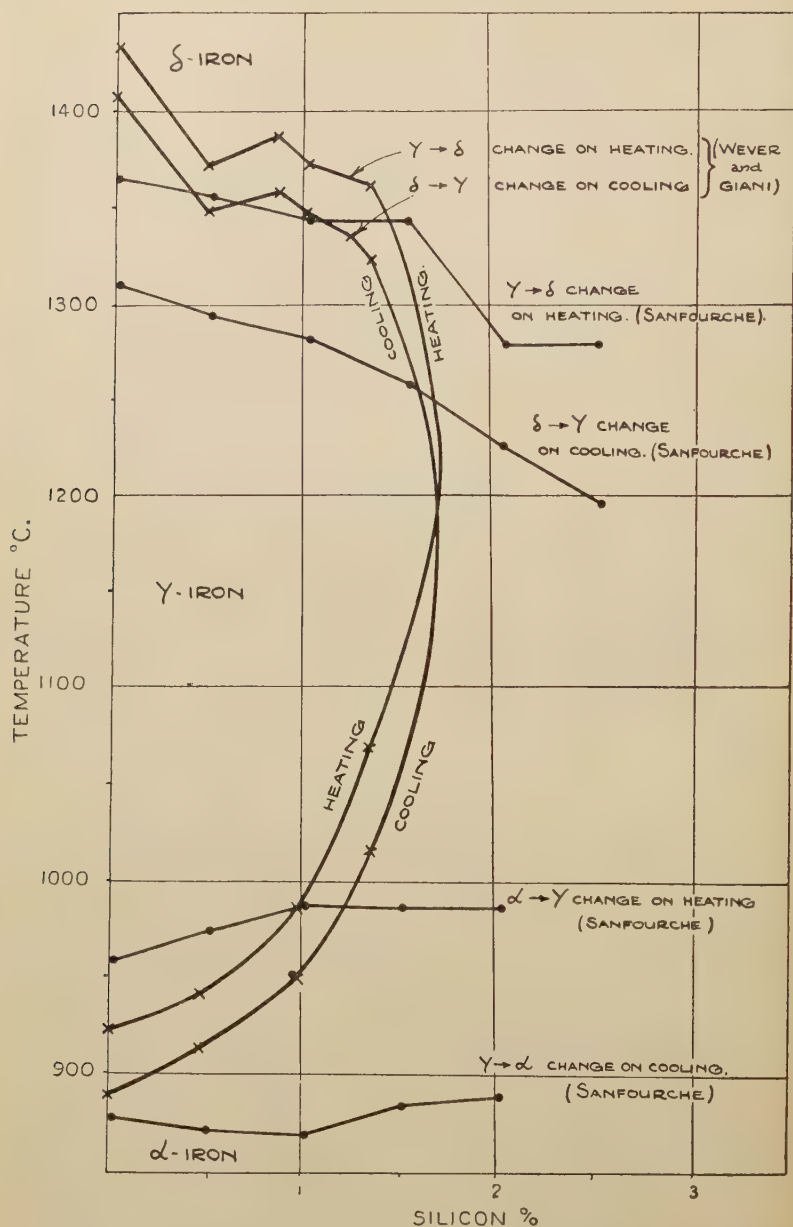


FIG. 12.—Effect of Silicon on the Temperature of the Pearlite Precipitation.

lowered from about 1380° C. with 0 per cent. of silicon to 1300° C. with 2 per cent. of silicon, as shown in Fig. 13. The difference between these two sets of results may be explained by assuming that carbon affects the temperatures at which the change takes place in the manner shown in Figs. 7, 8, and 9. In Fig. 8, for 2 per cent. silicon alloys, the point *N* has been placed at about 0.1 per cent. of carbon and 1300° C., and the α solid solution, which contains about 0.03 per cent. of carbon at 720° C., according to the recent work of Whiteley,⁽²⁰⁾ has been continued inwards—that is, for lower carbon contents—to meet the δ solid solution at high temperatures without any intermediate γ formation.

FIG. 13.—Effect of Silicon on the δ , γ , and α Allotropic Transformations.

A similar line has been drawn in the 4 per cent. silicon diagram with the saturation carbon content of the α and δ solid solutions increased. A comparison of the work of Ruer and Klesper⁽¹⁶⁾ with 0 per cent. of silicon, and Hanson⁽¹²⁾ with 2 per cent. of silicon, also suggests that the solubility of carbon in δ -iron increases as the silicon is increased from 0 to 4 per cent., since Hanson found a greater solubility of carbon in δ -iron than Ruer and Klesper did. That silicon increases the solubility of carbon in α -iron is also indicated by evidence given in section 12—namely,

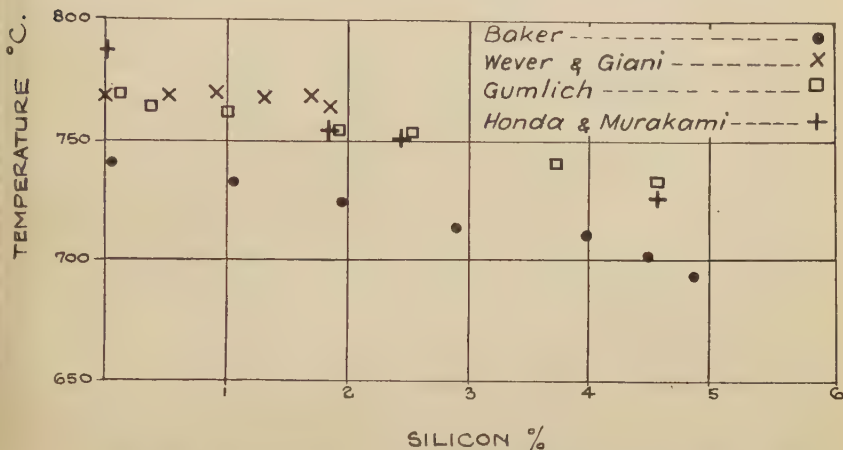


FIG. 14.—Effect of Silicon on the Temperature of the β - α Magnetic Change.

that 4 per cent. silicon grey cast irons can hold about 0.1 per cent. of carbon in solid solution.

Tamura⁽²¹⁾ has suggested that the solid solubility curve of carbon in δ -iron can be regarded as a continuation at high temperatures of the curve showing the solid solubility of carbon in α -iron.

(10) *Magnetic Change*.—In Fig. 7 the magnetic change M occurs at about 768° C. for 0 per cent. of silicon, and is lowered to 720° C. by meeting the line $G(S')S$, since it cannot occur until the γ - α change has taken place. The change appears to be lowered by about 10° for each 1 per cent. of silicon, according to the results of Baker,⁽²²⁾ Gumlich,⁽²³⁾ Wever and Giani,⁽¹⁷⁾ and Honda and Murakami,⁽¹³⁾ plotted in Fig. 14.

(11) *The Solidification Process of Medium and High-Silicon Grey Irons containing Normal (Coarse) Graphite, and the Effect of Graphite on the Combined Carbon Content.*—The experimental results summarised in the introduction (Section 1) may be explained by means of the constitutional diagrams in Figs. 7, 8, and 9, if the following assumptions are made. First of all, take the case of a molten cast iron containing a large number of minute graphite nuclei, sand-cast in the form of a 1·2-in. diam. bar and containing, say, 2 per cent. of silicon and 3 per cent. of total carbon. Such an alloy would commence to solidify along the line BC' in Fig. 8; it would deposit γ solid solution (finally of the composition E') along the line JE' , and would then deposit coarse graphite eutectic of the composition C' . The assumption is then made that if the graphite has been very finely divided the solid solution E' would have deposited graphite according to the line $(E')(S')$ —that is, the equilibrium line showing the solubility of graphite in γ -iron. In the case considered, however, the graphite is coarse, and it is consequently assumed that the graphite nuclei are insufficiently uniformly distributed to enable equilibrium to be set up. In other words, a condition equivalent to solid supersolubility is obtained, since if the graphite flakes are coarse the solid solution adjacent to them holds carbon in solid solution to the amount indicated by the line $(E')(S')$, while away from the graphite flakes it holds carbon in solid solution according to the line ES . Consequently, the combined carbon contents of such irons approximate to those obtained by solidification along the line ES . This has been indicated by dropping perpendicular dotted lines from E' showing the solubility of coarse graphite in γ -iron. This accounts for the fact that it is possible to get an almost completely pearlitic matrix with coarse graphite flakes, while ferritic-pearlitic matrices are obtained with fine graphite flakes.

On this view, the amount (as well as the distribution) of the graphite present should determine the graphitisation, or otherwise, of the combined carbon. This is borne out by the higher combined carbon contents of the low total carbon grey irons, especially the high-silicon irons, plotted in Fig. 1. It explains the stability of the carbide in steels where graphite is absent. It also explains the ferrite, then pearlite, then ferrite-graphite,

decarbonised edge found in certain types of malleable iron, as shown in Fig. 26 (Plate LV.). Such considerations could also affect determinations of the solid solubility of graphite, as, for instance, the positions of the lines $(E')(S')$ in Figs. 7, 8, and 9, and would explain Hanson's⁽¹²⁾ finding of an increase in carbide stability with a decrease in the total carbon content.

When the line SE is crossed on cooling, secondary cementite is deposited, which will decompose into graphite under ordinary conditions, but if manganese is only present in traces this secondary cementite is stable and is precipitated along the line SE and finally at the eutectoid S . In some cases it seems probable (in view of the pearlite-like form of the secondary cementite with its associated ferrite), as shown in Fig. 27, that this secondary cementite is not deposited along the line SE . In such cases it is suggested that the γ solid solution becomes supersaturated with respect to cementite, and only deposits it when the continuation of the line $G(S')S$ is crossed and the γ -iron changes into α -iron, causing the cementite to be thrown out of solid solution in the form shown in Fig. 27, which may be termed supersaturated pearlite.

The above form of secondary cementite—instead of the massive crystal boundary form—is the one most usually found in grey cast irons. Its presence in steels has been noted and commented on by Portevin.⁽²⁴⁾ When this secondary cementite graphitises, as it has done in the iron shown in Fig. 17, it deposits graphite on the eutectic graphite flakes, making them coarser and more continuous, and altering their typically eutectic formation. Figs. 28 and 29 (Plates LV. and LVI.) show irons practically identical in chemical composition with the iron shown in Fig. 17, with the exception that the iron in Fig. 28 contains 0.72 per cent. of combined carbon, and that in Fig. 29 1.18 per cent. of combined carbon. The differences in combined carbon are due to increasing amounts of secondary cementite. Conversely the iron in Fig. 29 contains little or no secondary graphite, while the irons in Figs. 28 and 17 contain increasing amounts of secondary graphite. A comparison of the three micrographs shows the effect of this secondary graphite in coarsening and linking up the eutectic graphite. Another reason why the coarse austenite-graphite eutectic is not often seen in a typically eutectic

formation is that the graphite nuclei necessarily present cause coagulation in a similar manner to that shown in the case of white irons in Figs. 24 and 25.

The solidification process of a 4 per cent. silicon iron is explicable in a similar manner by reference to Fig. 9. If the total carbon is above about 2.8 per cent. the matrix will be ferritic, according to Fig. 1, while if below this figure it will be pearlitic. This may be explained by the effect of the increased graphite content on the combined carbon (as indicated above), and also by the higher carbon irons containing more eutectic, whose heat evolution on solidification delays cooling, and consequently has an action similar to annealing with a resulting decomposition of combined carbon.

(12) *The Solidification Processes of Medium and High Silicon Grey Irons containing Supercooled (Fine) Graphite.*—Take the case now of an alloy containing 3 per cent. of carbon and 2 per cent. of silicon, sand-cast in the form of a 1.2-in. diam. bar, in which graphite nuclei in the melt are absent, having been destroyed, for example, by superheating. Such an alloy would commence to solidify along the line $B(C')$, and would finally deposit γ solid solution of the composition (E') and fine graphite eutectic of the composition (C'). If such an alloy contained only traces of manganese the secondary cementite would (as above) not decompose into graphite during cooling to room temperature. Consequently, instead of depositing graphite along the line (E')(S') such an alloy would deposit secondary cementite along the line ES and pearlite at the eutectoid temperature, or would deposit secondary cementite similar in form to that shown in Fig. 27, when the continuation of the line $G(S')S$ was crossed.

The microstructure of such an alloy (shown in Fig. 30) consists of supercooled graphite-austenite eutectic in between primary dendrites containing dark patches of secondary cementite of the form shown in Fig. 27. The combined carbon content of the alloy shown in Fig. 30 was 1.29 per cent., which agrees fairly well with the composition arrived at in the 2 per cent. silicon diagram from the intersection of the lines $S''E''$ and $C''E''$. The other elements present in the alloy were total carbon 3.02, silicon 1.83, manganese 0.03, sulphur 0.03, and phosphorus 0.03 per cent. Fig. 16 shows the microstructure of an iron practically

identical in composition with the exception that its combined carbon content was 0.62 per cent., due to the presence of 0.67 per cent. of manganese, which indirectly had caused the secondary cementite to graphitise during solidification. In the iron shown in Fig. 16, after the saturated γ solid solution had been deposited at (E'), graphitisation occurred along the line (E')(S'), and the solid solution deposited graphite on the nearest graphite nuclei—that is, on the fine graphite eutectic flakes bounding the dendrites, which, it will be seen (in Fig. 16), had become coarsened in the process. When the point (S'), which has a carbon content of 0.35 per cent. in the 2 per cent. silicon diagram, was reached, no further graphitisation occurred, owing to the relatively low silicon content, the low temperature and the moderately rapid cooling, and the alloy behaved like a 0.35 per cent. carbon steel and crystallised along the line (S') S , with the deposition of α -iron and final deposition of pearlite at the eutectoid S . It will be seen from the micrograph that the combined carbon content 0.35 per cent. is approximately what one would anticipate from the relative amounts of ferrite and pearlite in the dendrites. (The 0.62 per cent. of combined carbon found by analysis is higher, on account of the presence of coarse graphite associated with pearlite in other areas in the same specimen.) Examination under a higher magnification showed the presence of a certain amount of pearlite in the fine graphite eutectic part of the alloy.

Fig. 18 shows a supercooled graphite structure in an alloy of higher silicon content, containing total carbon 2.81, combined carbon 0.14, silicon 4.53, manganese 0.98, sulphur 0.03, and phosphorus 0.03 per cent. The alloy crystallised according to the supercooled fine graphite eutectic, consequently according to the 4 per cent. silicon diagram (Fig. 9) it would finally deposit solid solution of the composition E'' , which would deposit secondary graphite along the line (E'')(S') until the point (S')—which has a carbon content of about 0.17 per cent. for 4 per cent. of silicon (according to Fig. 9), and consequently somewhat less for 4.5 per cent. of silicon—was reached. The alloy would then change from γ solid solution into α solid solution, which, it is believed, can hold about 0.1 per cent. of carbon in solid solution at this temperature. A micrograph of the same alloy

(as that shown in Fig. 18), etched, is shown in Fig. 31. The black pearlite network, by rough calculation, accounts for a combined carbon content of 0.04 per cent., consequently the remainder of the combined carbon—namely, $0.14 - 0.04$ per cent. = 0.10 per cent.—is probably α solid solution. The black pearlite network, shown at 200 diameters in Fig. 32, has probably remained undecomposed on account of its association with the 0.03 per cent. of phosphorus present. It has also frequently been observed that crystallisation of the eutectic from centres sometimes commences according to the supercooled system and finishes according to the normal system, the result being central areas consisting of fine graphite and ferrite, contained in a network of coarse graphite and pearlite.

Another interesting feature, shown in Fig. 32, is the presence of a number of small circular and elliptical markings inside the austenite dendrites. It was at first thought that these markings were due to the δ - γ peritectic reaction not having proceeded to completion; it is now, however, believed that they are caused by the commencement of tarnishing.

(13) *Constitutional Diagram for Quenched Steels.*—Similar considerations of supercooling and supersaturation have been applied in the constitutional diagram shown in Fig. 15 to explain the effects of rapid cooling and quenching on the microstructures of steels.* In this figure the curve GS represents the temperatures and compositions at which the γ - α change would occur on very slow cooling or on heating. The curve has been produced from S to (K) to indicate temperatures at which the γ - α change would take place in supersaturated γ solid solutions. (The symbol (K) has been used to identify this supercooled curve to avoid introducing an entirely new symbol.) Supersaturated pearlite is shown in Fig. 27, and its formation is discussed in Section 11. $G'S'(K')$ represents a similar curve for normal rates of cooling. It will be noted that in this case the point S' is at 0.84 per cent. of carbon and 710°C. , in agreement with values found by Bardenheuer⁽²⁵⁾ from cooling curve determinations. The point S , on the other hand, is at 0.89 per cent. of carbon, which figure has usually been obtained from very slowly cooled or annealed steels.

* Since writing the present paper the author's attention has been drawn to a paper by Hallimond,⁽¹⁵⁾ in which the supersaturation theory of Miers is applied to the quenching of steels in a somewhat similar manner.

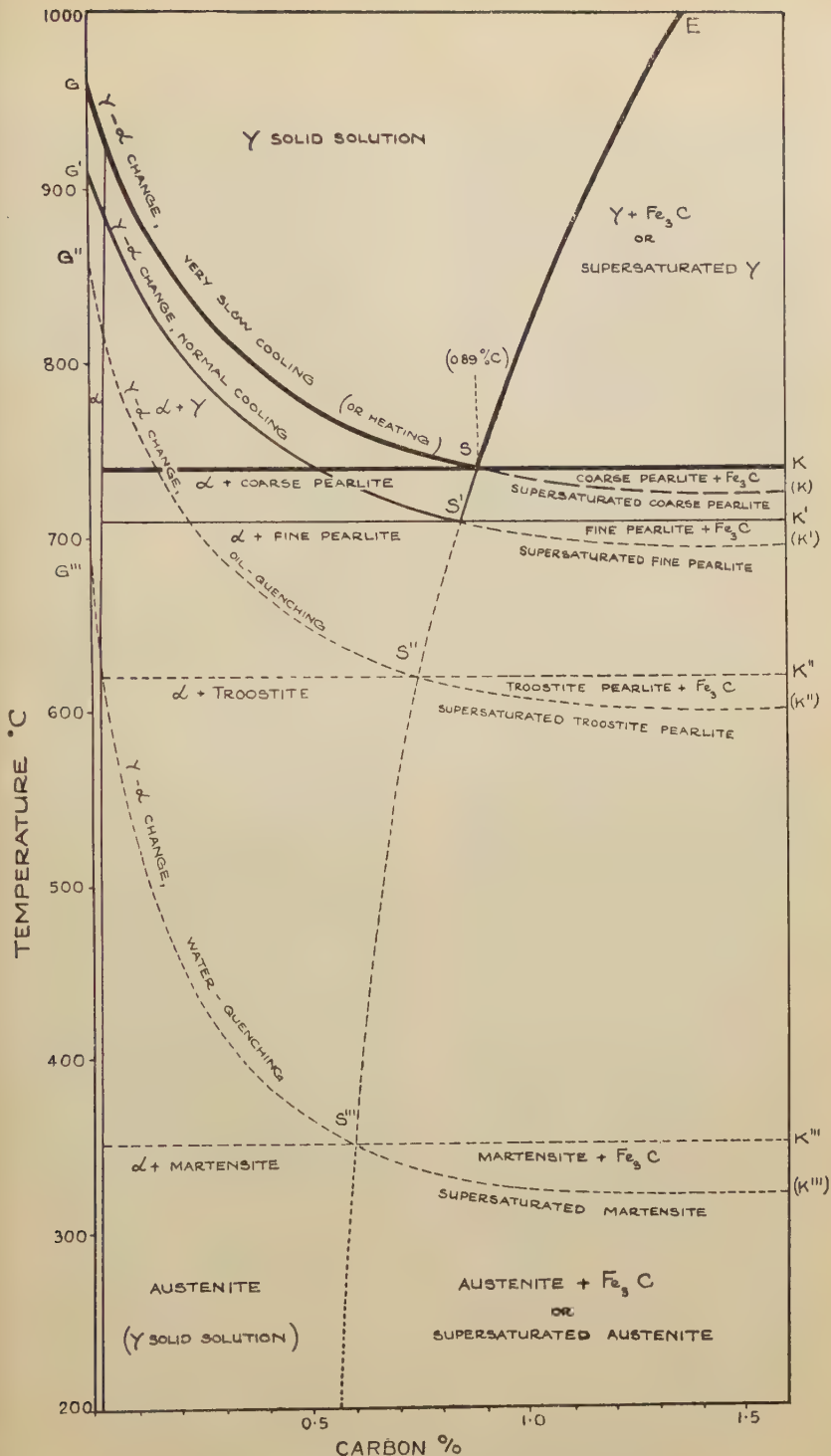


FIG. 15.—Constitutional Diagram for Quenched Steels.

Similarly, the curve $G''S''(K'')$ represents the depression of the γ - α change by rapid cooling, such as oil-quenching. This supercooling, consequent on rapid cooling, refines the pearlite structure so that troostitic pearlite is obtained. This refining action due to supercooling may be likened to that assumed for the austenite-graphite eutectic. Alloys to the left of the point S contain ferrite plus troostitic pearlite, while alloys to the right will contain troostitic pearlite plus cementite. Supersaturation is also indicated, as above. The temperature 620° C. for the line $S''K''$ is taken from the work of Portevin and Garvin,⁽²⁶⁾ who found that rapidly cooled steels which exhibited a change point above this temperature contained troostitic pearlite, while steels in which the change point was suppressed below this temperature had martensitic structures.

The curve $G'''S'''(K''')$ represents the lowering of the γ - α change due to very rapid cooling, such as water-quenching. The point G''' has been placed at 685° C. in view of the work of Hanemann and Schrader,⁽²⁷⁾ who found that however rapidly they cooled pure iron they could not depress the γ - α change below 685° C. The same authors found that for hyper-eutectic carbon steels the change was suppressed to about 300° to 400° C. (average, 350° C.) if martensitic microstructures resulted. The carbon content of the γ solid solution at 350° C. will presumably be considerably less than 0.89 per cent., since the known part of the curve ES shows that the solubility decreases systematically with a decrease in temperature. The curve ES has consequently been extrapolated as shown in Fig. 15, and at 350° C. the solid solubility has been given a value of 0.6 per cent. of carbon. This value has been deduced from a consideration of the microstructures obtained by Hanemann and Schrader on water-quenched steels of various carbon contents between 0 and 1.6 per cent., which have been interpreted as showing the presence of ferrite and martensite in water-quenched steels containing carbon below 0.6 per cent., and of martensite plus cementite in steels containing more than that amount of carbon.

It is assumed that in martensite the γ - α change has taken place at such a low temperature that the carbon atoms have not been able to move and coalesce, and consequently remain atomically dispersed. If it were possible to suppress the γ - α change completely in low-carbon steels, unsaturated austenite would

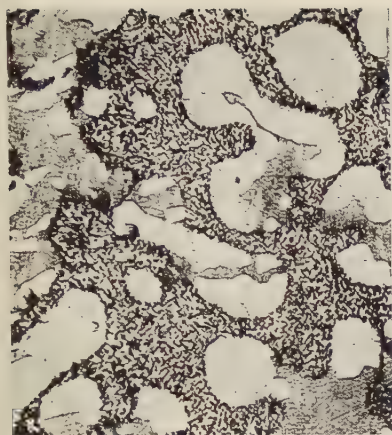


FIG. 16.—Supercooled (fine) graphite, ferrite and pearlite in medium-silicon grey iron. $\times 200$. T.C., 2.91 per cent.; C.C., 0.62 per cent.; Si, 1.82 per cent.; Mn, 0.67 per cent.; S, 0.03 per cent.; P, 0.03 per cent.



FIG. 17.—Normal (coarse) graphite in pearlite in iron of similar composition to that in Fig. 16. $\times 200$. T.C., 2.94 per cent.; C.C., 0.80 per cent.; Si, 1.70 per cent.; Mn, 1.00 per cent.; S, 0.03 per cent.; P, 0.03 per cent.

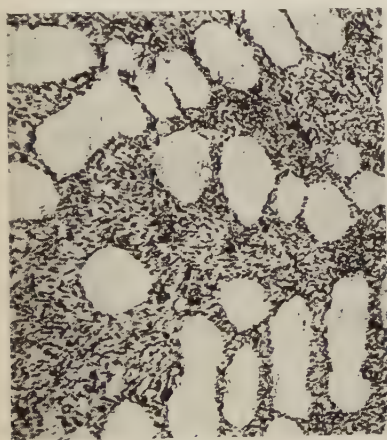


FIG. 18.—Supercooled (fine) graphite in ferrite in high-silicon grey iron. $\times 200$. T.C., 2.81 per cent.; C.C., 0.14 per cent.; Si, 4.53 per cent.; Mn, 0.98 per cent.; S, 0.03 per cent.; P, 0.03 per cent.



FIG. 19.—Normal (coarse) graphite in ferrite, also patches of phosphide and pearlite, in iron of similar composition to that in Fig. 18. $\times 200$. T.C., 2.71 per cent.; C.C., 0.17 per cent.; Si, 4.46 per cent.; Mn, 1.10 per cent.; S, 0.03 per cent.; P, 0.30 per cent.

(All above specimens etched in alcoholic picric acid.)

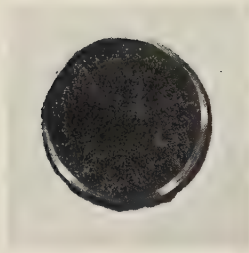


FIG. 20.—Close-grained dull “sooty” fracture, typical of grey irons in Series A. (Supercooled fine graphite type.) Natural size.

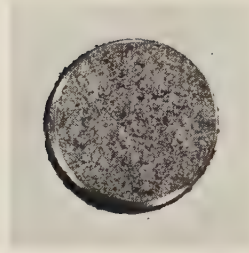


FIG. 21.—Coarse-grained fracture containing shining graphite flakes, typical of irons in Series B. (Normal coarse graphite type.) Natural size.



FIG. 22.—Large network, typical of irons in Series A. (Supercooled fine graphite type.) Cementite and phosphide white. $\times 25$. T.C., 3.02 per cent.; C.C., 1.29 per cent.; Si, 1.83 per cent.; Mn, 0.02 per cent.; S, 0.03 per cent.; P, 0.03 per cent.



FIG. 23.—Small network, typical of irons in Series B. (Normal coarse graphite type.) Cementite and phosphide white. $\times 25$. T.C., 2.79 per cent.; C.C., 1.18 per cent.; Si, 1.67 per cent.; Mn, 0.47 per cent.; S, 0.28 per cent.; P, 0.03 per cent.

(Figs. 22 and 23, etched in nitric acid, sp. gr. 1.20.)

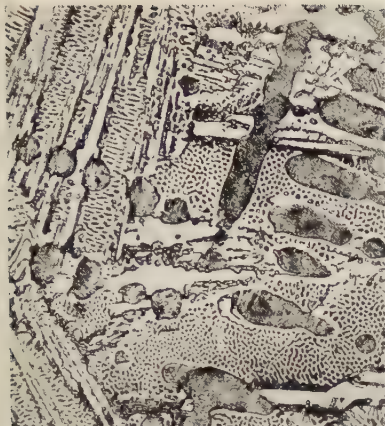


FIG. 24.—Supercooled eutectic in white iron. $\times 300$. T.C., 3.90 per cent.; Si, 0.63 per cent.; Mn, 0.03 per cent.; S, 0.03 per cent.; P, 0.03 per cent.

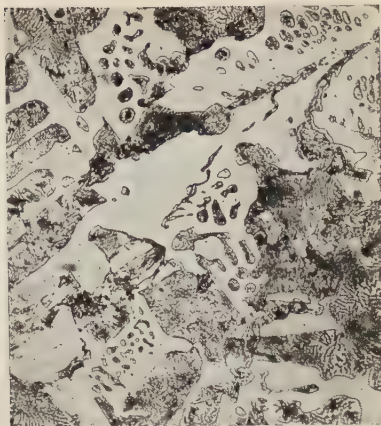


FIG. 25.—Coalesced eutectic in white iron of similar composition to that in Fig. 24. $\times 300$. T.C., 3.91 per cent.; Si, 0.61 per cent.; Mn, 0.28 per cent.; S, 0.13 per cent.; P, 0.10 per cent.

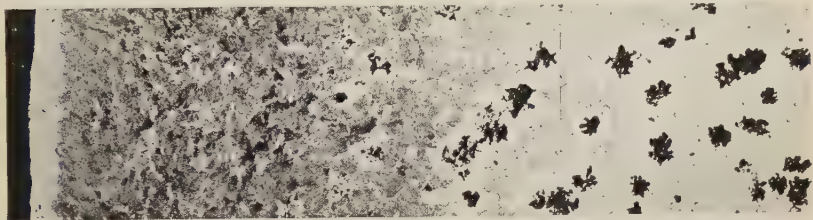


FIG. 26.—Decarbonised edge of malleable iron, showing graphitisation of pearlite by graphite nodules. $\times 50$.

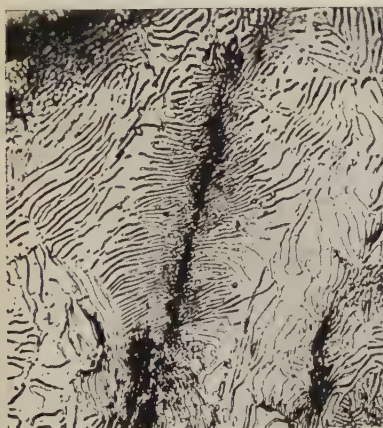


FIG. 27.—Secondary cementite in form of super-saturated pearlite. This constituent appears as partly resolved dark patches in Figs. 29 and 30. $\times 1000$.



FIG. 28.—Normal graphite eutectic with secondary cementite partly graphitised in iron of similar composition to that in Fig. 17, except for the combined carbon. $\times 200$. T.C., 2.79 per cent.; C.C., 0.72 per cent.; Si, 1.72 per cent.; Mn, 0.50 per cent.; S, 0.13 per cent.; P, 0.03 per cent.

(All above specimens etched in alcoholic picric acid.)

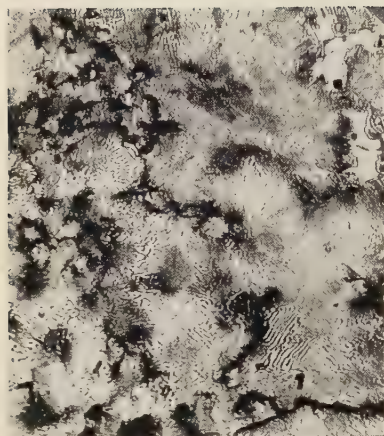


FIG. 29.—Normal graphite eutectic with secondary cementite not graphitised in iron of similar composition to those in Figs. 17 and 28, except for the combined carbon. $\times 200$. T.C., 2.79 per cent. ; C.C., 1.18 per cent. ; Si, 1.67 per cent. ; Mn, 0.47 per cent. ; S, 0.28 per cent. ; P, 0.03 per cent.



FIG. 30.—Supercooled graphite eutectic with secondary cementite not graphitised in iron of similar composition to Fig. 16, except for the combined carbon. $\times 200$. T.C., 3.02 per cent. ; C.C., 1.29 per cent. ; Si, 1.83 per cent. ; Mn, 0.03 per cent. ; S, 0.03 per cent. ; P, 0.03 per cent.



The same specimen as Fig. 18, showing pearlite network (black).

FIG. 31. $\times 25$.

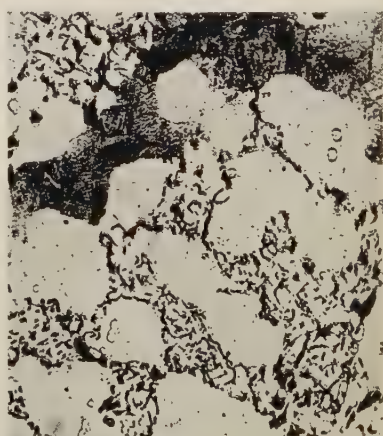


FIG. 32. $\times 200$.

result. In high-carbon steels it is possible to suppress the change more or less completely, and austenite plus needles of cementite or supersaturated austenite is then obtained. If chromium, manganese, or certain other elements are alloyed with steels they lower the temperature of the γ - α change, consequently slower rates of cooling are sufficient to give structures similar to those obtained in carbon steels with quicker rates of cooling. Carbon, by lowering the γ - α change, acts in a similar manner, and facilitates quenching.

The above explanation differs from that given by Hanemann and Schrader, who postulated the existence of ϵ - and η -irons; they constructed an equilibrium diagram for temperatures below the normal eutectoid temperature, in which they indicated by means of phase lines the temperatures and compositions over which these ϵ and η phases are stable.

(14) *Summary*.—Constitutional diagrams have been constructed for iron-carbon alloys containing 0, 2, and 4 per cent. of silicon, respectively. In these diagrams both normal and supercooled systems have been shown for the austenite-graphite eutectic and for the austenite-cementite eutectic. Grey irons have been assumed to crystallise according to the normal graphite-austenite system when graphite nuclei are present in the melt. Such irons contain coarse graphite flakes and tend to be pearlitic. Conversely, when graphite nuclei are absent, supercooling occurs, and the graphite is deposited in the form of exceedingly fine flakes which tend to be associated with ferrite. In the case of white irons, it has been assumed that nuclei cause the precipitation of small amounts of graphite eutectic, which in turn cause the precipitation of white iron eutectic at the maximum possible temperature and with consequent coalescence. In grey irons, the tendency for coarse graphite to be associated with pearlite, and fine graphite with ferrite, has been explained by assuming that the γ solid solution adjacent to the graphite flakes holds carbon in solid solution according to the (lower) solid solubility of graphite, while that away from the graphite flakes holds carbon in solid solution according to the (higher) solid solubility of cementite. Consequently, the coarser and the fewer the graphite flakes the higher the percentage of carbon in solid solution. The temperatures and compositions in the 0, 2, and 4 per cent. silicon constitutional diagrams have been estimated in most

cases from existing data. The lowering of the change points in steels due to quenching has also been represented in a constitutional diagram as a form of supercooling.

The micrographs were taken by Mr. L. W. Bolton, and the analyses were carried out by Mr. C. Rowley. The author thanks the Council of the British Cast Iron Research Association for permission to publish this paper.

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CORRESPONDENCE.

Mr. E. ADAMSON (Sheffield) wrote: The author has taken a great deal of time and trouble to collect the information which makes up his investigation, and he is to be congratulated thereon. The paper is, of course, of greater academic than practical interest. The influence of silicon on solidification, and also the influence of "quenching," or what the author calls supercooling, on fracture is common knowledge amongst workmen. In the first place, the term "supercooling" is somewhat misleading; it is more generally known on the pig beds as quenching or chilling. With the prefix "super" it might be misunderstood to be specially *slow* cooling, which is not what the author means.

The author's test-bars are, of course, correctly speaking, "synthetic" pig iron, some of the samples being actually *true* "semi-steel"; they can therefore only be compared with samples made from similar material, and are not strictly comparable with commercial pig irons of similar analysis. Swedish white iron is usually charcoal cold-blast iron, and the fact that it, a blast-furnace product, is white shows that the temperature of production was very low. On the other hand, Armco iron is essentially a mild steel made at a high temperature, and when the white iron and steel, together with the ferro-silicon, were melted together, all the carbon would be in solution as carbon produced at a low temperature. He (Mr. Adamson) had repeatedly shown that when ferro-silicon is added to white iron the structure of the resulting sample is not so open as would be expected from the silicon and sulphur contents, for additions of silicon in this way do not tend materially to *open* the grain and produce "coarse" graphite, such as is found in No. 1 and No. 3 pig irons. This is not theory, but statement of fact.

In Figs. 20 and 21, the author shows what he calls a close-grained dull sooty fracture typical of "quenched" (supercooled) iron, and also what is termed a coarse-grained fracture containing shiny graphite flakes, which he states are *normal coarse-grained* graphite; but from the size of the bars shown by the author the results obtained are just what would be expected under the circumstances. Fig. 20 shows the natural "quenched" fracture for grey iron, and Fig. 21 is a natural slowly-cooled iron with additions of silicon, but if the sample shown in Fig. 21 had been produced from a grey foundry iron of the same silicon and sulphur contents the fracture would have been considerably more open, so that what the author calls a coarse-grained fracture is in fact a close fracture when judged against ordinary commercial foundry irons.

The author mentions on p. 444 that some of his samples contained

0·30 per cent. of phosphorus, but he does not say how it was added. If this phosphorus were added in the form of pure phosphorus it would have a slightly different influence from that which it would have if added in the form of pig. In Fig. 23 the sulphur is given as 0·28 per cent., but this is presumably a slip for 0·028 per cent.

On p. 443 the author states that the explanation advanced by certain investigators is that the refining of graphite is due to the graphite nuclei in the melt, but the author can be assured that this statement does not apply to his experiments. Graphite could not exist in his Swedish white iron, otherwise it would not be white. The carbon in the Swedish white iron, therefore, exists in solid solution, and on precipitation, whether through excessively slow cooling *per se*, or through additions of silicon, the carbon when freed would be *fine* graphite. It is very satisfactory to know that the author believes that graphitisation is due to *expansion on cooling*, the expansion with the additions of silicon being of course due to the silicon.

With regard to Figs. 3 and 4, the peculiar internal mottled appearance of the test-bar is well known to those who have had to do with the refining of pig iron; Poole showed a number of examples of the mottled fracture in the test-bar with the outside edge grey, similar to that shown in Fig. 3 by the author. As the author accepts the theory of graphitisation due to "expansion," he will also see that this explains the phenomenon, to which he draws attention, of internal *pressure* on cooling which has been intensified by "quenching" (supercooling). Fig. 4 shows a natural division between white and mottled in a test-bar of the size shown when the analysis brings the sample within the range of the chilling irons, but in the latter there is not such a distinctly marked line of division between the white and the grey; there is usually a "mottle-off."¹

The combined carbon contents of the silicon series A and B shown in Fig. 1 are very interesting, and show that, even with that care which would be exercised by the author in melting the irons used, it is impossible to obtain a given ratio of combined carbon to silicon with the same percentage of graphite, or the same ratio of graphite to combined carbon with the same percentage of silicon. That the same combined carbon with a given silicon content is obtained with varying percentages of graphite or total carbon proves that silicon, as suggested previously by Pearce,² in no way controls the total carbon or the ratio of the total to combined carbon even in synthetic pig iron, and therefore it is not possible to run the foundry simply on silicon contents. The more the author investigates cast iron the more he will realise that, even with constant analyses and as far as possible the same heating and cooling conditions, exactly the same results cannot be repeatedly obtained. He will not find any white or mottled fractures

¹ E. Adamson, *Journal of the Iron and Steel Institute*, 1906, No. I. p. 75 (see Table B, p. 92).

² *Journal of the Iron and Steel Institute*, 1928, No. II. p. 73.

of commercial foundry irons and castings corresponding to the analyses given for series A ; if carefully examined, some of the grey fractures in series B will be found to be slightly mottled, otherwise the combined carbon figures cannot be correct.

The AUTHOR, in reply, wrote that he thought the substitution of the word "quenching" for "supercooling" would be most undesirable. From melts of ferro-silicon, white iron, and Armco iron, he could produce open or coarse fractures at will, according to the order in which the constituents of the charge were melted. He did not agree that the coarse-grained fractures in his test-bars could be considered as close fractures when judged against ordinary commercial foundry irons of similar cross-section. The phosphorus was added in the form of 20 per cent. ferro-phosphorus. The sulphur content of 0.28 per cent. in Fig. 23 was the correct figure, and in conjunction with the relatively low manganese of 0.47 per cent. accounted for the high combined carbon content.¹ While the carbon in Swedish white iron was ordinarily in the combined form, it deposited graphite nuclei in the melt when ferro-silicon was added to it.

Figs. 3 and 4 represented the *extreme* types of mottled fractures that could be obtained, and were sketched from actual test-bars. Mr. Pearce was well aware of the results shown in Fig. 1 at the time he wrote the paper referred to. He had examined a large number of commercial castings and pig irons, and, allowing for differences in structure due to differences in the rate of cooling, &c., he had found their fractures, microstructures, and properties to be intermediate between those given for Series A and Series B. Some of the bars in Series B contained secondary cementite ; they were not mottled in the ordinary sense.

This paper will be submitted for further discussion at an Additional Meeting at Birmingham on September 26, 1929 (see *Journal of the Iron and Steel Institute*, 1929, No. II.).

¹ The point is dealt with in a paper presented by the author to the Institute of British Foundrymen in June 1929 (see *Foundry Trade Journal*, 1929, vol. xli. Aug. 1, pp. 79-83).

BRITTLENESS IN MILD STEEL.¹

By G. R. BOLSOVER, F.INST.P. (SHEFFIELD).

THE occurrence of cases of brittleness in articles produced from dead soft steel of satisfactory quality necessitated the investigation of the circumstances under which it would be produced. This condition was always found in articles which had been formed and subsequently critically heated, such as would be the case in the production of pressings subsequently heated for galvanising or other purposes. Under such conditions, whilst the material as a whole remains perfectly ductile, any attempt to straighten out the bent strip results in cracking along the groove with comparatively light pressure. The fracture occurs irrespective of the rate at which the load is applied, and, when conditions are such as to produce brittleness, the fracture of the steel is coarsely granular as compared with the normal fibrous break obtained on fracturing other portions of the same steel by repeated bending, which portions fail to exhibit brittleness, owing to their not having been deformed prior to heating and testing.

The results of the investigation about to be set forth have subsequently been found to confirm work done on the Continent,² but in view of the fact that some of the features disclosed are novel, and that the continental work referred to has received little or no attention in Great Britain, the major portion of the results obtained will be given in detail.

It was found that, given the right conditions of forming and subsequent heating, brittleness of the type mentioned could be produced in all qualities of soft steel, and it appeared that this was due to the imposition of tensile stresses on a portion previously subjected to compression, or that the effect was a fundamental property of cold-worked material. It was thought that if the latter should be the case the most ready means of determining the

¹ Received January 16, 1929.

² E. Maurer and R. Mailänder, *Stahl und Eisen*, 1925, vol. xlv. p. 409. P. Dejean, *Revue de Métallurgie, Mémoires*, 1927, vol. xxiv. p. 415.

influence of the various factors would be to perform Izod impact tests on samples prepared from a bar of dead soft steel, and that has been adopted as the standard material for the greater part of the work. The composition of the steel was as follows :

	%
Carbon	0·14
Manganese	0·60
Silicon	0·037
Sulphur	0·035
Phosphorus	0·015

As a preliminary, and in order to prove that the effect was not limited to any one quality of soft material, tests were performed on samples of dead soft steel, free-cutting steel, and Armco iron in the following conditions :

- (1) Air-cooled from 950° C.
- (2) „ „ 950° C. and reheated to 300° C.
- (3) „ „ 950° C., stretched 10 per cent. and reheated to 300° C.
- (4) „ „ 950° C. and stretched 10 per cent.

The results obtained are set out in Table I., and indicate that for the conditions of cold-work and reheating to which the samples were submitted, all three qualities show very distinctly the bad effect of combined cold-work and subsequent reheating on the brittleness of the steel.

The effect of stretching alone is evident, although not very marked, in the material used for the general investigation. The impact value of Armco iron has fallen on simple reheating, but in no case is the loss of impact strength at all comparable with that obtained by combined deformation and reheating.

In view of these results it was decided to concentrate on the dead soft steel for the further work, and samples of this were treated as follows : one batch was stretched 2 per cent. of its length ; while another batch was stretched 10 per cent. of its length, and was subsequently reheated to various temperatures prior to testing at room temperature, to determine the effect of two different amounts of extension and the various temperatures of reheating. The results are given in Table II. A reheating temperature of 350° C. was not exceeded, as preliminary tests had shown that the maximum effect was obtained with a temperature of reheating between 250° C. and 300° C.

The results indicate that 2 per cent. extension has very little effect on the brittleness of the steel, and confirm that 250° to

TABLE I.—*Izod Impact Tests on Various Steels.*

Material and Treatment.	Izod Impact Values. Ft.-lb.			
	1.	2.	3.	Average.
<i>Dead Soft Steel.</i>				
(1) A.-C. 950° C.	87	94	94	90·3
(2) " " and reheated 300° C. .	90	93	87	90·0
(3) " " { stretched 10 per cent. and reheated 300° C.	15	5	13	11·0
(4) " " { and stretched 10 per cent.	72	73	72	72·3
<i>Free-Cutting Steel.</i>				
(1) A.-C. 950° C.	90	89	92	90·3
(2) " " and reheated 300° C. .	88	91	91	90·0
(3) " " { stretched 10 per cent. and reheated 300° C.	6	6	7	6·3
(4) " " { and stretched 10 per cent.	23	51	22	32·0
<i>Armco Iron.</i>				
(1) A.-C. 950° C.	91	94	100	95·0
(2) " " and reheated 300° C. .	40	82	36	52·7
(3) " " { stretched 10 per cent. and reheated 300° C.	7	10	14	10·3
(4) " " { and stretched 10 per cent.	20	26	20	22·0

A.-C. = air-cooled.

TABLE II.—*Izod Impact Tests on Dead Soft Steel.*

Reheating Temperature after Stretching. ° C.	Izod Impact Values. Ft.-lb.			
	1.	2.	3.	Average.
<i>Stretched 2 per cent. before Treatment.</i>				
Nil	92	92	94	92·7
100	97	102	93	97·3
200	48	96	96	80·0
250	94	104	94	97·3
300	93	106	97	98·7
350	96	96	93	95·0
<i>Stretched 10 per cent. before Treatment.</i>				
Nil	70	71	74	71·7
100	28	28	73	43·0
200	30	24	74	42·7
250	11	12	9	10·7
300	8	30	15	17·7
350	87	96	88	90·3

300° C. is the most satisfactory temperature for the production of the condition aimed at.

A further series of tests was performed with various degrees of extension, all samples being subsequently reheated for $\frac{1}{2}$ hr. to 250° C. ; the results are given in Table III. :

TABLE III.—*Izod Impact Tests on Dead Soft Steel.*

Degree of Stretching. %.	Izod Impact Values. Ft.-lb.				
	1.	2.	3.	4.	Average.
Nil	85.0	93.0	87.0	86.0	87.75
5	67.0	72.5	87.5	23.0	62.5
10	13.5	25.0	11.0	11.5	15.25
15	6.0	9.0	9.0	8.0	8.0
20	10.0	7.0	9.0	9.0	8.8

It was now considered that the conditions for the production of brittleness were sufficiently well established, and they were standardised at 15 per cent. extension and subsequent reheating to 250° C. for $\frac{1}{2}$ hr. A further series of tests was arranged to determine the influence of the testing temperature subsequent to such treatment.

EFFECT OF TEMPERATURE OF TESTING.

Samples of the same dead soft steel were tested at various temperatures in each of the following conditions :

- (1) Normalised from 950° C.
- (2) „ „ 950° C. and stretched 15 per cent.
- (3) „ „ 950° C., stretched 15 per cent. and reheated for 30 min. to 250° C.
- (4) „ „ 950° C. and tempered for 30 min. at 250° C.

For testing purposes the samples were heated in a water-bath to the required temperature and held for 10 min. prior to placing in the Izod machine ; the grips of the latter were also heated to approximately the same temperature. While these precautions prevent, so far as possible, the loss of heat during the rapid transference of the sample from the bath to the testing machine, and up to the time of fracture, it is obvious that, with the exception of the tests which were actually performed at atmospheric temperatures, the actual temperature of testing will be slightly different from that stated in each case. The results of these

tests are set out in Table IV., but the effect is more clearly shown on the curves plotted in Fig. 1.

TABLE IV.—*Effect of Testing Temperature on Izod Values.*

Testing Temperature. ° C.	Izod Impact Values. Ft.-lb. Condition of Test-Pieces—											
	Normalised from 950° C.			Normalised from 950° C., stretched 15%.			Normalised from 950° C., stretched 15% and reheated for 30 min. to 250° C.			Normalised from 950° C. and tempered for 30 min. at 250° C.		
	1.	2.	Average.	1.	2.	Average.	1.	2.	Average.	1.	2.	Average.
0	90.0	89.0	89.5	28.0	21.0	24.5	7.5	7.5	7.5	91.0	91.0	91.0
11	82.5	87.0	84.8	31.0	29.5	30.3	5.0	7.0	6.0	91.5	90.0	90.8
16	90.0	89.0	89.5	74.0	29.0	52.5	4.5	7.0	5.8	87.5	84.0	85.8
21	86.0	87.0	86.5	74.0	38.0	56.0	8.0	9.5	8.8	90.0	91.0	90.5
26	84.0	85.0	84.5	75.0	76.0	75.5	7.5	7.5	7.5	89.0	90.0	89.5
31	86.0	87.0	86.5	73.0	73.0	73.0	12.0	25.0	18.5	88.0	89.0	88.5
41	81.5	85.5	83.5	76.0	75.0	75.5	14.0	20.0	17.0	87.0	85.0	86.0
61	80.0	80.5	80.3	71.5	71.0	71.3	68.0	38.0	53.0	88.0	82.0	85.0
81	87.0	84.0	85.5	75.0	76.0	75.5	62.0	66.0	64.0	79.0	82.0	80.5
100	82.0	81.0	81.5	74.0	75.0	74.5	60.0	57.0	58.5	79.0	81.0	80.0

It will be seen that the embrittling effect already dealt with is again very much in evidence, but that with the rise of testing temperature this brittleness disappears until at 80° C. comparatively normal values are obtained. In addition, the same effect is to be noted in the sample normalised and stretched without subsequent reheating, but in this case the descending portion of the curve is pushed over towards the zero temperature line. In fact, it will be obvious from a study of this particular curve that this steel, tested within the range of what may be considered normal room temperatures, could very readily give a value down to 30 ft.-lb. or as high as 70 ft.-lb. From the form of these curves it would appear probable that were the testing temperatures of the samples reduced sufficiently, even in the normalised condition, a drop in impact value similar to that displayed by the previous two curves would be obtained, and that the brittleness effect was not so much the production of a brittle state as the raising of the temperature at which such brittleness was apparent in dead soft steel. As a matter of interest, tensile tests were performed on material as normalised, normalised and stretched, and normalised, stretched, and tempered; the values are given in Table V.

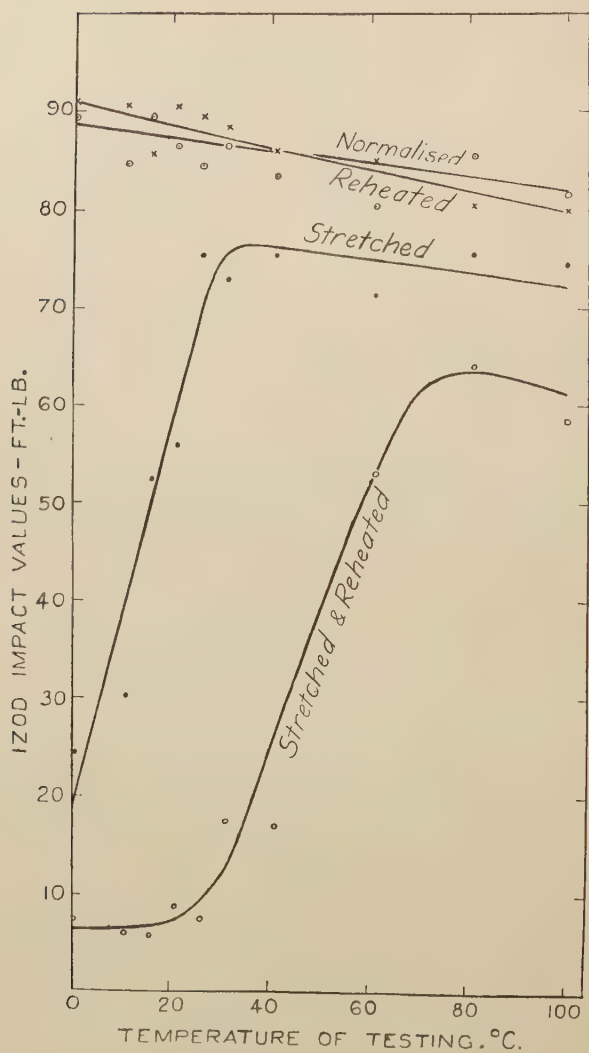


FIG. 1.

TABLE V.—*Mechanical Properties of Treated Specimens.*

Treatment.	Yield Point, Tons per sq. in.	Maximum Stress, Tons per sq. in.	Elongation, %—		Reduction of Area, %
			On 2 in.	On $4\sqrt{A}$.	
Normalised	17·6	26·5	38·5	45·7	71·8
Normalised and stretched	30·0	30·8	20·0	27·9	66·1
Normalised, stretched, and tempered	32·9	34·6	17·5	22·1	65·3

INFLUENCE OF INITIAL CONDITION OF THE STEEL.

It was next decided to determine the influence of the initial condition of the steel on this particular form of brittleness; similar tests were performed on the same material after hardening by quenching in water from 950° C. and tempering to 650° C., and also after cooling slowly in borings.

The effect of the initial condition, as represented by these two conditions and also by the normalised material, is indicated in Table VI., and in the curves reproduced in Fig. 2.

TABLE VI.—*Izod Impact Tests on Samples Tested after Stretching and Reheating, in Three Different Initial Conditions of Heat Treatment.*

Testing Tempera- ture. ° C.	Izod Impact Values. Ft.-lb. Initial Conditions—										
	Water-Quenched 950° C., tempered 650° C.				Normalised 950° C.			Cooled slowly in Borings from 950° C.			
	1.	2.	3.	Average.	1.	2.	Average.	1.	2.	3.	Average.
0	76·0	31	...	53·0	7·5	7·5	7·5	2·0	1·5	...	1·8
11	83·0	20	38	47·0	5·0	7·0	6·0	...	...	...	...
16	...	...	...	...	4·5	7·0	5·8	...	...	...	...
21	85·0	79	...	82·0	8·0	9·5	8·8	2·0	2·5	...	2·3
26	...	...	...	...	7·5	7·5	7·5	...	...	...	...
31	...	...	...	...	12·0	25·0	18·5	...	...	...	...
41	79·0	77	...	78·0	14·0	20·0	17·0	2·5	4·5	...	3·5
61	81·5	71	...	76·3	68·0	38·0	53·0	15·5	8·0	...	11·8
71	71·0	...	...	71·0	...	...	...	11·0	...	...	11·0
81	...	...	...	...	62·0	66·0	64·0	34·0	20·0	...	27·0
85	...	...	...	...	...	...	...	25·5	...	...	25·5
91	72·0	...	...	72·0	...	...	...	45·5	15·0	...	30·3
95	73·0	...	...	73·0	...	...	...	20·0	41·0	60·5	40·5
100	77·0	77	...	77·0	60·0	57·0	58·5	69·0	54·0	...	61·5
121	64·0	...	...	64·0	...	...	...	60·5	...	...	60·5

From these results it is evident that the more slowly cooled material, as illustrated by that cooled in borings, gives a curve

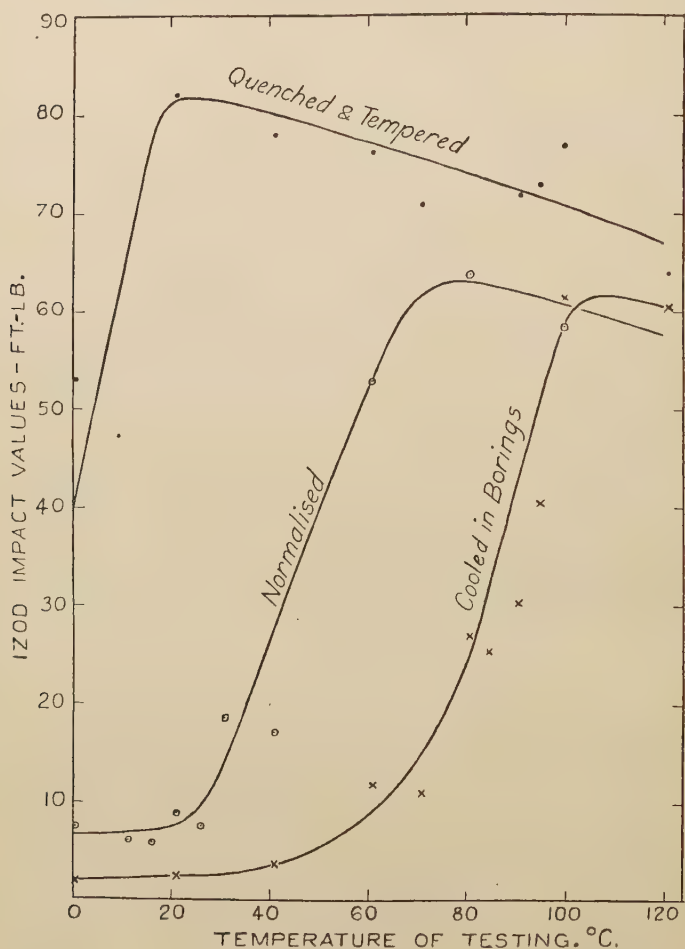


FIG. 2.

which is displaced so that still higher temperatures of testing are required to obtain satisfactory impact values, whilst hardening and tempering produces a condition of the steel which results in the displacement of the curve in the opposite direction, resulting in the brittle condition being only produced—even when stretched

and reheated—at about 0° C. The variable values obtained between 0° and 20° C. in this condition, and similar effects on some of the other curves, are apparently due to those tests being performed at temperatures corresponding with the steeply sloping portion of the curves, when a very slight variation in the condition will give either a high or low value.

THE EFFECT OF PHOSPHORUS ON BLUE-BRITTLINESS.

In the original work on blue-brittleness referred to previously it was noticed that an increase in the phosphorus content appreciably increased the brittleness of the strip, and in view of this three steels of varying phosphorus contents were prepared and submitted to further tests; the analyses of the steels were as follows:

	No. 1. %	No. 2. %	No. 3. %
Carbon	0·14	0·19	0·20
Manganese	0·37	0·45	0·35
Silicon	0·041	0·065	0·093
Sulphur	0·064	0·070	0·100
Phosphorus	0·020	0·055	0·107

In order to ensure that the same condition of stretching should apply as in the case of the steels of low phosphorus content, a set of samples from the above three steels was tested at room temperature after stretching to 5, 10, 15, and 20 per cent., respectively, of their original length, and reheating to 250° C. Such tests indicated, as will be seen from Table VII., that the previously accepted conditions of test would be satisfactory, and accordingly samples from each steel were tested at various temperatures under those conditions, the results being given in Table VIII., and in Figs. 3, 4, and 5.

It is evident that whilst test results in the normalised condition indicate at higher temperatures a comparatively small fall in impact value with increasing phosphorus content, the differences increase at lower temperatures. Also, in the stretched condition, and particularly in the stretched and tempered condition, the low values persist to higher temperatures with an increase in the phosphorus content, and whereas with low phosphorus a temperature of testing is reached at which the results after stretching and

TABLE VII.—*Izod Impact Tests on Phosphorus Steels.*

Degree of Stretching.	Izod Impact Values. Ft.-lb.		
	1.	2.	Average.
<i>Phosphorus Steel No. 1.</i>			
%			
5	78	78	78.0
10	20	18	19.0
15	11	10	10.5
20	10	11	10.5
<i>Phosphorus Steel No. 2.</i>			
%			
5	17	14	15.5
10	6	7	6.5
15	12	8	10.0
20	5	7	6.0
<i>Phosphorus Steel No. 3.</i>			
%			
5	9	10	9.5
10	8	5	6.5
15	4	3	3.5
20	3	5	4.0

TABLE VIII.—*Izod Impact Tests on Phosphorus Steels 1, 2, and 3, Tested at Various Temperatures in Differing Conditions.*

Testing Temperature. ° C.	Izod Impact Values. Ft.-lb. Conditions of Test-Pieces—								
	Normalised 950° C.			Normalised 950° C., stretched 15% and tempered 30 min. at 250° C.			Normalised 950° C. and stretched 15%.		
	1.	2.	3.	1.	2.	3.	1.	2.	3.
0	84.0	86.5	47.0	6.0	3.5	2.5	16.5	6.0	4.5
		71.5	47.0				15.0		
8	86.0	88.0	41.0	5.0	4.5	3.0	21.5	4.0	3.0
		74.5	78.0						
20	81.0	51.0	57.5	14.5	5.0	3.0	34.0	6.0	3.0
		84.0	39.0						
40	77.0	76.5	53.5	24.0	11.0	11.5	58.0	22.0	11.0
						10.5			
60	75.0	77.0	69.5	33.0	16.0	7.0	60.5	41.0	14.5
						7.0			
80	77.0	73.0	68.0	59.0	37.0	12.0	58.5	51.0	23.5
100	77.5	72.0	68.5	65.5	50.0	18.0	59.5	50.5	27.0
120	74.0	71.0	65.0	62.5	49.0	23.0	55.5	50.0	34.5
140	73.0	74.5	68.0	57.5	51.5	20.0	57.5	50.0	34.5

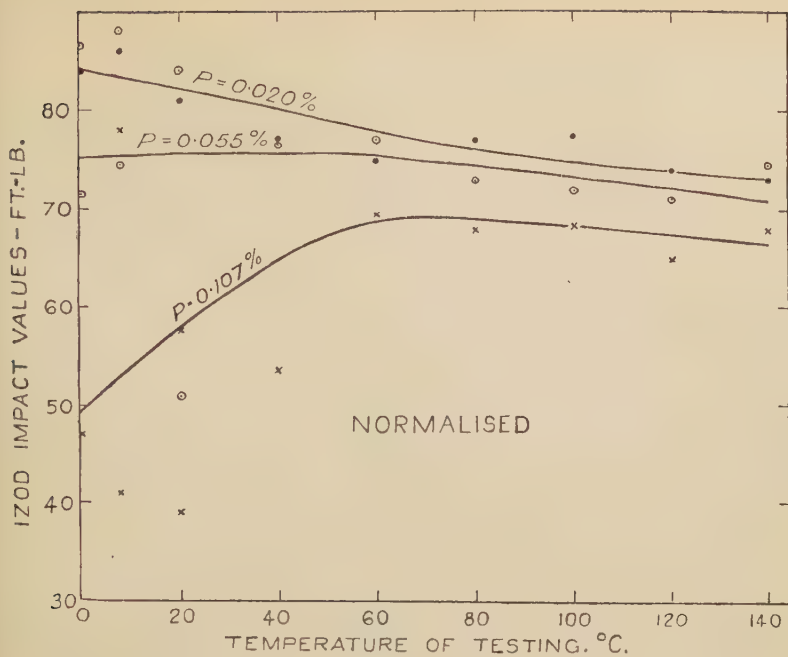


FIG. 3.

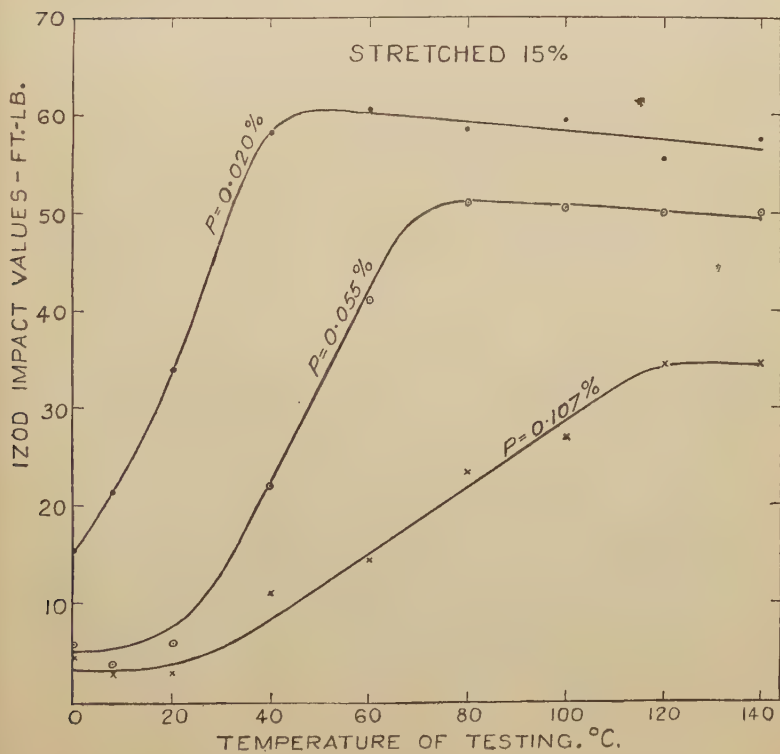


FIG. 4.

reheating equal those in the normalised condition, except for the slight loss due to induced hardness by cold-working, the values

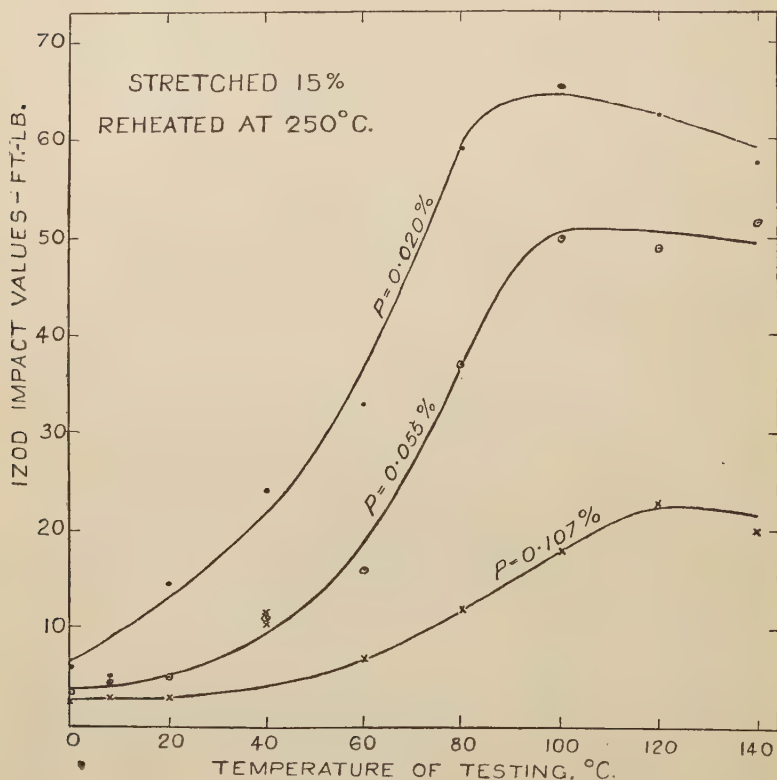


FIG. 5.

obtained with high percentages of this element remain considerably reduced, even when tested at temperatures higher than 100° C.

THEORETICAL CONSIDERATIONS.

A consideration of the theoretical aspects of the foregoing cannot be essayed without first attempting to explain the effects produced by cold-working such material. As is now well known, deformation in the cold results in an increase in the hardness

and a reduction in the ductility of the steel, these effects being increased by subsequent reheating to temperatures such as those dealt with above. Various attempts have been made to explain these increases in hardness along the lines of crystal structure and atomic arrangements. The author would suggest that a more satisfactory explanation of the brittleness in question can be derived from a consideration of the grosser effects of cold-working.

The original increase in hardness by cold-working can be readily explained by the gradual using up of the planes of least resistance to slip, which would result in increased stresses being required to cause further deformation. Apart from the movement along the planes of crystals most readily responsive to such stresses, there will always be in stressed materials a movement of a grosser type along certain planes, notably the planes of shear stress.

It is a well-known fact that on reheating cold-worked material it is possible to obtain either recrystallisation or grain-growth, according to the amount of stress applied and the subsequent temperature of reheating, these effects being visible under the microscope at temperatures down to 400° C. In view of this, it is possible that sub-microscopic recrystallisation takes place at appreciably lower temperatures, and it is now suggested that a temperature of reheating of 250° to 300° C. is sufficient to induce recrystallisation along the planes of maximum movement in deformed material. Such recrystallisation along these planes without recrystallisation of the mass would result in an internal strained condition of the steel, and the brittleness dealt with above is due, in the author's opinion, to this state of internal stress.

On testing steel in such a condition at gradually increasing temperatures it is obvious that a temperature will be reached at which the mobility within the mass is sufficient to allow of the dissipation of these internal stresses, following which the impact value of the material will rise to normal limits.

The reason why steel which has been deformed and not reheated recovers its ductility at an earlier stage than the reheated material would appear to be that owing to no recrystallisation having occurred along the planes of maximum strain, the internal strain is not by any means so great as is the case with the material

which has been reheated subsequently to stressing. As even the normalised material is in a slight state of strain within the mass, due to cooling conditions, it is fair to assume that a still further reduction in the temperature of testing would result in such steel showing low impact values—a fact which has been established by other workers.

The next point at issue is the difference obtained in tests under the conditions dealt with between material in differing initial conditions. The data recorded above indicate that a normalised steel is more prone to brittleness than one which has been hardened and tempered, and the effect is still more marked in a steel which has been slowly cooled prior to stressing and reheating.

It is well known that the coarser the grain of the material the greater is the liability to local deformation on stressing, and if the foregoing explanation of the behaviour of stressed and reheated steel be accepted, this provides a ready explanation of the difference in the behaviour of the three different conditions of mild steel.

SUMMARY.

1. Mild steel becomes brittle if deformed beyond certain limits and reheated to approximately 250° C., while the undeformed portions of the same steel remain perfectly ductile.

2. If cold-worked and reheated as above, impact values are lowered from approximately 90 ft.-lb. to less than 10 ft.-lb. when tested at room temperature.

3. The impact resistance increases with a rise of testing temperature, until at 80° C. the reduction is only such as would be expected, in view of the increased hardness induced by cold-working.

4. For different conditions of the steel, the temperature at which the induced brittleness is lost varies. Mild steel in the hardened and tempered condition remains ductile to a lower temperature than similar steel in the normalised condition, whilst original slow-cooling induces brittleness at a higher temperature.

5. Normalised steel which has been subsequently worked and reheated becomes brittle at a higher testing temperature than that which has been worked only, and this in turn at a higher temperature than the normalised material.

6. Increasing phosphorus contents increase the loss in ductility in each of the above conditions, but this is particularly marked in steels which have been reheated after cold-working.

7. Apart from their influence on the question of impact testing, the results given are of vital interest in connection with pressed articles, particularly if reheated after pressing, in view of the increasing use of such articles for vital parts, for lifting chains, particularly where they are reheated after use, for rivets, and for numerous other purposes where hitherto the ductility of dead soft steel has not been questioned.

The author wishes to express his thanks to Messrs. S. Fox & Co., Ltd., Stocksbridge Works, near Sheffield, in whose Research Department this work has been carried out, for permission to publish the data recorded, and also to his colleagues who have helped in the experimental work ; he would particularly mention in this connection Mr. R. D. Pollard, Assoc.Met., of the Research Department, and Mr. H. Lismer Test-House Manager.

DISCUSSION.

Mr. A. ALLISON (Sheffield) said the paper was an interesting record of some properties of mild steel which were very familiar to those concerned with steel pressings. Not long ago he had some pieces of mild press-work steel put before him which pressed beautifully, but when the articles were enamelled at a temperature of about 300° C. they were so extremely brittle that if one attempted to shear a piece with hand-shears the steel fractured like glass.

There was one aspect the author had not touched on, but which he thought was very important—namely, the question of grain-size; he might have added to the interest of the paper by showing illustrations of the grain-size.

The steel experimented with by the author contained carbon 0.14 and manganese 0.6 per cent. He believed it was generally recognised that the steel which, above all others, was liable to grain-growth, was that which lay in the carbon range 0.05 to 0.13 per cent., with a manganese range of, probably, 0.35 to 0.40 per cent. It seemed to him, therefore, that the author had experimented with a steel which was just outside the range within which grain-growth was liable to take place, although some of its effects might occur; he would have obtained more pronounced results, probably, had he operated within the grain-growth range. In support of that, it would be observed in Table I. that the Armco iron, even when normalised at 950° C. and reheated at 300° C., showed marked brittleness—what, quantitatively, might be called brittleness, though he hardly thought it could be called practical brittleness. That iron had probably the coarsest grain-size of any of the materials experimented with. Probably the finest grain-size would be produced by the water-quenching, and the coarsest by cooling slowly in the furnace, so that it would appear from a comparison of Tables IV. and VI. that the effect of grain-size was reflected in the corresponding impact figures.

Coming to the theoretical considerations, he ventured to suggest that the brittleness described by the author was closely related to a phenomenon well recognised in steel pathology, and known as Stead's brittleness. It appeared to him that there were two kinds of brittleness. The author had tackled one variety, which he thought was the kind most frequently found in practice. The brittleness produced by straining or cold-working steel and then tempering was true Stead's brittleness. Then the author showed that merely reheating to 300° C. produced a certain degree of brittleness. Personally, he could not suggest how the two were related, except that some change in the ferrite was produced by tempering at 300° C.

For the phenomenon of Stead's brittleness he had ventured to

suggest elsewhere¹ an explanation on the following lines. When strained steel was examined under a microscope, the visible strain lines, by their very visibility, indicated that portions of a crystal had slipped over one another; and he suggested that that process of slipping indicated an actual liquefaction, immediately followed by a quenching effect, which was actually regelation. In support of that, he contended that it was difficult to conceive that if a portion of a crystal slipped over another portion under the influence of stress, the two portions would adhere together afterwards, unless something of the nature he suggested took place. He carried the suggestion further and said the brittleness increased with the grain-size, because, although under the microscope one saw only linear dimensions, actually those slip-planes varied as the square of the diameter of the crystals.

Another point was that recent experiments, particularly those of Edwards, Pfeil, and Carpenter, had shown that tensile strain produced a definite critical degree of deformation different from that produced by cold-rolling. He suggested that, in the case of tensile strain, the crystals were more free to select their favourable orientations than in cold-rolling, where probably all the crystals were compelled to undergo deformation.

Tempering at 300° C. seemed to be an essential part of the brittleness, and the figures given in Table I. indicated that tempering after normalising without straining had a more decided effect on the Armco iron than on the low-carbon steel. Since the phenomenon normally occurred in steels containing 0.1 per cent. of carbon or less, it would appear that the cause was located in the ferrite crystals and that some change was produced at 300° C. The expulsion to the boundaries of such carbide as was present seemed to be a part of the process.

The theory he put forward had at least one virtue, in that it agreed to some extent with that suggested by the author. Granted that the material of the slip-bands underwent sub-microscopic crystallisation, one might suggest that the temperature of 300° C. produced sufficient recrystallisation to weaken the welding between the crystal portions, without being sufficient to re-form definite crystals with consequent boundary strength. He could not agree that internal strains would account for the brittleness; in fact, he suggested that a paragraph in the paper itself, in which the author referred to rising temperature imparting increased mobility, controverted that statement.

Mr. T. H. TURNER (Birmingham) said the paper showed that there was a maximum liability for cracking or brittleness to take place somewhere about 200° C.

Fig. A showed the liability of mild steels to develop strain-etch markings. The two phenomena must be very closely connected, because the work done on strain-etching showed, not only that the

¹ *Iron Age*, 1926, vol. cxviii., July 6, p. 73.

phosphorus content was of importance, but that the effects of the previous treatment of the steel were similar—that is, quenched steel would not give the strain-etching marks, or the peculiar brittleness described, and so on. At the top of the curve there was no liability to produce strain-etching, and down at the bottom, between 150° and 250° C., there was the maximum liability.

Jevons had reproduced illustrations¹ of a series of tensile specimens which, after annealing, had been strained to different degrees; they would explain the variations found in Tables I. and II. of

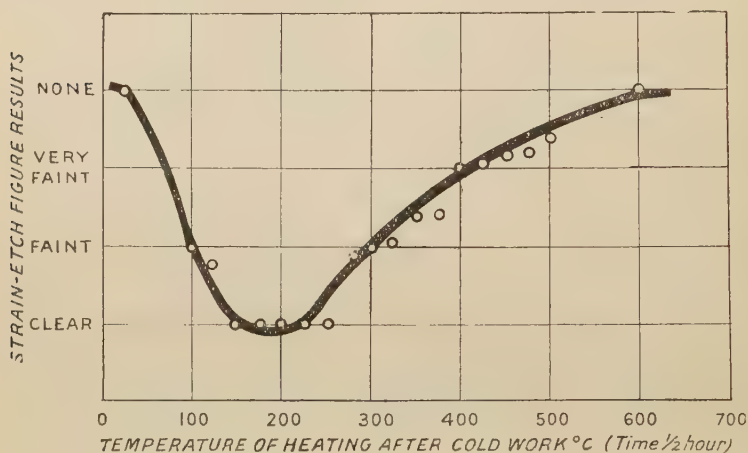


FIG. A.—Extended Experiments on the Effect of Varying the Low Temperature of the Heat Treatment necessary before Strain-Etching. (Comparative observations after 72 hr. in the strain-etching solution.) (E. W. Fell, *Carnegie Scholarship Memoirs*, 1927, vol. xvi. p. 101.)

Mr. Bolsover's paper. After straining, they had been heated to the critical temperature range which the author had used, and they had then been etched for a long time in Fry's reagent. The wedge-shaped deformations produced in the steel were very localised, and the whole of the test specimen was not equally strained between the yield point and some 5 per cent. elongation. In most of the cases there were quite large areas which were not strained. The author had taken very similar test-pieces, except that they were circular, while those of Jevons were flat; the latter might therefore be regarded as sections from the author's test-pieces. After straining, the author had cut Izod test-pieces from the strained material. As was well known, the Izod test only showed the property of the material just at the bottom of the notch, and therefore it would be seen that the author might have

¹ *Journal of the Iron and Steel Institute*, 1925, No. I., Plate XXII., Figs. 1 to 5.

prepared several test-pieces in which the bottom of the notch was actually unstrained material; in only one or two might he get, at those low extensions, strained material at the bottom of the notch. That was borne out by Table II.; at 200° C., one test on a given specimen gave a figure of 48 and the other 96, a difference of 100 per cent., whereas where there was no reheating there was remarkable uniformity. The same could be said for the 10 per cent. elongation, but there the liability to strike one of the strained areas was greater, so that the results tended to be lower, although there was again a great difference between the results from the same specimen.

Turning to Table III., one found exactly the same difference on the dead soft steel. With no stretching the specimens gave extraordinarily uniform results. With 5 per cent. stretching there was a marked difference, the figures varying from 87 to 23, while with 10 per cent. the variation was between 25 and 11, which were again very marked percentage differences. He thought the same explanation applied in that case also. He therefore agreed with the remark in the author's theoretical considerations, that the grosser effects of cold-working must be regarded as of great importance here, but he would supplement that by saying that the grosser effects were obviously connected with the space-lattice structure of the material.

The question arose of whether this brittleness was transitory. Mr. Sutton¹ had referred to a brittleness in pickled steel which would depart by simply leaving the specimen for a few days, or by boiling it in water. Had the author any evidence that the brittleness in strained and heated steels was transitory? After reading Mr. Bolsover's paper, he dug out some specimens, four years old, and tried to find whether they were still brittle. So far as he had gone they were not, but he could not say he had gone far enough. He had not found the signs of extreme brittleness which the author showed.

The German work to which the author referred was concerned with boiler steels. There had been great trouble through mysterious cracks in carbon steel boilers, and the recommendation made was that since that type of material could not be relied on an alloy steel should be used to overcome the difficulty. The German workers showed that 2 per cent. nickel steel and 5 per cent. nickel steel gave practically the same good results as the usual mild steels, so far as freedom from that type of brittleness was concerned. The phenomenon under discussion was linked up with the "ageing" of boiler steels. There could be no doubt that strain-etching, the brittleness in question, and ageing were at bottom due to the same causes. Stromeyer had recently pointed out that the defect of cracks in boilers was by no means so scarce as was imagined, and the insurance companies were anxious about it. Mr. Bolsover's investigation of the causes of that type of brittleness

¹ See Sutton's paper, this volume, p. 179.

might therefore also be of use in connection with the choice of materials and processes for boiler manufacture.

Mr. J. A. JONES (Research Department, Woolwich) said that in a paper which Dr. Greaves and he had read before the Institute,¹ they had described some work on the effect of cold-rolling on the impact figure of mild steel. Reheating cold-worked material at 250° C. resulted in an increase in the maximum load and a consequent lowering of the impact figure, which was an effect similar to increasing the degree of cold-rolling. That displaced the temperature/impact-figure curve to the right, as illustrated by the author, and as was the case of mild steel cold-rolled by different amounts. The annealed material, if tested at temperatures below atmospheric, would show a curve identical in form, but placed farther to the left, as was suggested in the author's paper.

Another interesting point was the difference in the values which could be obtained for apparently identical material when notched-bars were tested at temperatures about atmospheric. In the testing of notched-bars cut longitudinally from mild steel of about the carbon content described by the author, it was found that, for material where there could not be any variation in the properties to warrant the difference, one could get either a high or a low value for the energy absorbed. Intermediate values were very rarely obtained. The effect was probably due to a difference in the mode of deformation.

Tests which were carried out on annealed mild steel reheated to 250° C. and tested afterwards without overstraining at temperatures about and below atmospheric showed that that treatment tended to eliminate the high figure. It was necessary, in order to form a definite conclusion, to carry out a large number of tests. The few tests he had been able to undertake showed there was a tendency to eliminate the high figure.

It was of interest to note the effect of phosphorus, which was rightly regarded as an element inducing brittleness in steel. High phosphorus content showed a pronounced effect in increasing relative ageing brittleness. The author carried out a heat treatment recognised as one that would increase the ductility of a steel—hardening and tempering—and that treatment decreased the susceptibility of the steel to ageing brittleness. He would therefore suggest that the addition of an element which was known to increase the ductility of the steel might also reduce the susceptibility of the steel to the form of brittleness described. A paper on boiler steels,² published in America, showed that the effect in question was considerably reduced in some nickel steels, but perhaps the addition of chromium might produce the effect at a lower cost. It would be of interest to learn

¹ *Journal of the Iron and Steel Institute*, 1925, No. II. p. 123.

² C. McKnight, "Alloy Steel for Boiler Construction," *Transactions of the American Society for Steel Treating*, 1928, vol. xiii. p. 638.

if the author had any information about the susceptibility of alloy steels to that form of brittleness.

Mr. T. M. SERVICE (Glasgow) said that quite recently he had been investigating the same point as the author. There could be no doubt that the particular class of steel described, containing approximately 0.1 per cent. of carbon and low in manganese, was very susceptible to the particular form of brittleness with which the paper dealt. He had investigated various boiler-plate steels which contained about 0.2 per cent. of carbon, and it was only in some cases that that brittleness was obtained; it did not occur in every case. On the Continent a steel which did not possess that brittleness was being advertised; he understood it was a steel which was very highly deoxidised. About 90 per cent. of the steel in Great Britain was open steel, and very little attempt was made to deoxidise that material. Boiler-plate material was not so completely killed as that used for ordinary forgings, for guns or anything like that, but was more completely killed than the ordinary ship-plate quality; occasionally one might get one charge more deoxidised than another, and that might be the charge which was satisfactory and did not have the property complained of. He suggested, therefore, that possibly the quality of the steel had more to do with the brittleness than the chemical composition. It might be of interest to make a dead-melted steel with 0.1 or 0.2 per cent. of carbon and determine whether it still possessed those properties.

Mr. J. H. WHITELEY (Consett) said he presumed that Mr. Bolsover cooled the samples in air after heating them to 250° C., so that they would cool fairly slowly through the 80° range in which most of the brittleness was removed. If so, it was rather surprising that the brittleness still remained, and he would like to know if it was increased by quenching from 250° C. in water. He was particularly interested in the paper as it concerned the galvanising process for sheets. Occasionally, extreme brittle material was produced, usually with the thicker sheets. He thought that the reason was, in such cases, that the temperature reached in annealing had not been sufficient to remove all cold-work in the first place, and then, subsequently, the sheet, owing to its thickness, did not reach the temperature of the galvanising bath in the short time of immersion. Mr. Bolsover's work indicated that it only reached 250° C. A peculiar feature of that brittleness was, however, that it was not removed until the steel had been heated to above 500° C. The bends were still bad when the sheet was heated for long periods at lower temperatures. In that respect the brittleness appeared to differ from that produced by Mr. Bolsover. Did the annealing temperature required depend upon the time the steel was held at 250° C.?

Mr. H. O'NEILL (Manchester) said that on p. 485 it was stated that by reheating the cold-worked material to the region of 250° C. the hardness was increased. Personally, he regarded that as a half-truth. If the hardness tests were conducted at a very low Brinell load the treated metal would be found to be softer. He had deformed some crystals of iron some years ago,¹ and by conducting scratch tests on them found that softening proceeded at those low temperatures. The loads used for scratching were very small—equivalent to a $\frac{P}{D^2}$ value of 0.5. The matter had also been dealt with very fully by Pfeil,² who had more or less settled it. It could not be said that by heating to 250° C. the hardness was either increased or decreased; one could only say that the "hardenability" of the steel had been changed. He therefore disagreed with one of the speakers in the discussion, who stated that by heating the cold-worked steel at 250° C. one in effect increased the amount of strain-hardening in it, or, rather, that the treatment was equivalent to giving it more cold-rolling. Pfeil's work showed that that was not the case. The amount of cold-work in the steel could in a sense be represented by the lowering of the Meyer n value of the ball test. Pfeil had shown that by heating worked iron to 250° C. the n value was *increased*, which meant that that annealing had just the reverse effect to putting in more cold-work.

He thought that it was necessary to emphasise these effects associated with the Brinell test, and due to the Brinell hardness number obtained with different loads giving different values. Testing the material with very low loads would show softening at 250° C., though with a normal load a somewhat higher value might be obtained.

It had also been stated³ that low-temperature annealing of cold-worked iron caused a *decrease* of electrical resistivity. One might expect that to be associated with a decrease of hardness.

Mr. T. H. TURNER (Birmingham) remarked that Mr. O'Neill had discussed a theoretical aspect of the hardening effect of strain in words which appeared to show that the local strain did not actually harden the steel. He would point out that the local hardening due to strain had been definitely proved by Fell.⁴

Mr. E. W. COLBECK (Northwich) said he had recently been faced with a problem in regard to 22 and 24-gauge sheet material, with very low carbon and manganese content. Drums were made of that

¹ "The Effect of Annealing on Cold-Worked Single Crystals of Silico-Ferrite," *American Institute of Mining and Metallurgical Engineers. Iron and Steel Technology in 1928*, p. 229.

² *Iron and Steel Institute, Carnegie Scholarship Memoirs*, 1927, vol. xvi. p. 153.

³ *American Institute of Mining and Metallurgical Engineers. Institute of Metals Division*, 1927, p. 388.

⁴ *Iron and Steel Institute, Carnegie Scholarship Memoirs*, 1927, vol. xvi. p. 101 (see Fig. 18, Plate XIV.).

material by seaming and closing up the seams tight, and there was a certain critical deformation which one could put on with the seaming machine which resulted in the drum seams cracking when they were filled with a liquid at about 330°C . It might have been expected that the effect of a 330° or 340°C . treatment on a 22-gauge sheet would be to anneal it. The drums waited 6 hr. before they cracked, the temperature being then just about 200°C . The cracking could be prevented by altering the pinch in the seaming machines, so that it appeared that the cracking had something to do with a critical deformation and a critical range of temperature.

Mr. F. W. HARBORD, C.B.E. (Past-President), said there was one very practical consideration which arose out of the author's first conclusion that mild steel when stressed beyond certain limits and reheated to approximately 250°C . became brittle. That brittleness depended upon the material being stressed beyond certain limits, but many stamped articles were severely stressed and afterwards japped, and although he did not know the exact temperature used during that process, he thought it would be somewhere about the above temperature, and if those stampings were brittle when subjected to further stress, fracture might occur.

Many deep stampings were not subjected to further stress after japping or similar treatment, and the danger in those cases would not arise, but in many cases they were, and results might be serious. He had had one or two failures brought to his notice which he thought might possibly be due to that cause.

An important point was whether the brittleness referred to was permanent or transitory, as in the latter case, if the articles were left for a few days before being further stressed, the danger of failure might be removed.

Professor T. TURNER (Member of Council) said some of those present might remember the very interesting paper on the subject now under discussion, and the beautiful illustrations in it, which was presented by Dr. Stead a number of years ago. One of the characteristics of the brittleness shown by Dr. Stead was the right-angle fracture in the thin mild sheet—a fracture which, as far as he knew, one saw only in such cases. Such brittle sheet steel could recover its ductility, of course, under suitable treatment.

Taking an example from other metals, the British Non-Ferrous Metals Research Association had recently done some interesting work in connection with sheathing for cables which, when of pure lead, often gave trouble with fractures. A very important improvement had been effected by the addition of a small quantity—of the order of only 0.1 per cent.—of either cadmium or tin. Another case was that of zinc; that metal was rolled, and a great deal of press-work was done with it. With pure zinc one might get trouble from fractures and

brittleness, but the addition of a very small quantity of another element, such as copper, made that zinc better than the pure material. He did not know if it had been tried, but he thought the suggestion made by Mr. Turner was worth consideration—namely, that if to these mild steels a small quantity of a suitable element were added there might not be so much trouble with brittleness. Whether as much as 1 per cent. of added element would be required was doubtful; judging by experience in other cases, less than 1 per cent. might be quite sufficient to improve the quality of the material.

Mr. BOLSOVER, in reply, said Mr. Allison had commented on the fact that grain-size was not shown by micrographs. While he had not shown it in that way, he had given results regarding it, which Mr. Allison had confirmed; he had tested steel in three different conditions of grain-size, and the results, as instanced by the three different initial conditions, were recorded in Fig. 2. He agreed that, generally speaking, low carbon and manganese steels gave a greater grain growth than normal steel and steel of the type he had used. The Continental steels did show that type of brittleness considerably more than the English steels; they were lower in carbon and equally low, or lower, in manganese. He chose the particular steel he had used (and this answered one of Mr. Service's comments as well) because it was definitely a solid steel. He hesitated to use the "open" type of steel because it introduced heterogeneity, which might have some influence on the subsequent test according to whether the notch was situated in the chilled portion or the segregate portion.

Mr. Allison had said there were two kinds of brittleness; personally he came across many more than that. All he had done in the paper, however, was to attempt to get to the bottom of one of them. He would be pleased to supply Mr. Allison with samples of a dozen different types.

He did not propose to go into the amorphous theory again. Mr. Allison had suggested that the phenomenon occurred only in mild steel, but he could assure him there was evidence that it also occurred in other than mild steels. One reason why he wanted to get his paper in print was that the number of variables one could apply with regard to this form of brittleness made it almost impossible for any one worker to get through the amount of work necessary in a reasonable time, and he hoped as a result of the paper somebody would do a little of the work for him and publish the results.

He could not quite understand Mr. Allison's theory that minute grain growth in the amorphous material caused the brittleness. A sub-microscopically fine material was a strong material, and he did not see why it should be brittle on that account. He did see reasons why that alteration in grain should cause internal strain, however, and he thanked Mr. Turner for his contribution on that point. Personally, he thought the results Mr. Turner had obtained confirmed the theory which he

himself had put forward—namely, that internal strain was the cause of the brittleness.

Mr. Turner had suggested that the grosser effects referred to in the paper were dependent on the space-lattice; that was an arguable point, but personally he did not think so. He thought that whatever the type of space-lattice there would still be those grosser effects. There was bound to be deformation of the space-lattice, but he did not think the brittleness was dependent on the space-lattice but on the planes of maximum strain, and those were independent of the lattice.

The question whether the brittleness was transitory had been raised. He thought the opposite effect applied. When cold-worked material was reheated to 250°C . there was an increase in the elastic limit, in the yield point, and in the maximum stress in tension, and a reduction in the ductility; hence, he said, the material was harder after heating to 250°C . One could get the same effect by ageing at room temperatures. If cold-rolled strip was sent to a customer's works and not checked until a couple of months had elapsed, it would be found to be outside the specified range, owing to its having been stored in a warehouse at room temperatures. It was only fair to assume that the room-temperature ageing effect on the brittleness would occur in the same way as it would on heating to 250°C ., as would be done to harden cold-rolled strip. It was possible that the brittle condition was not confined to dead soft steels, and would be produced by ageing alone, apart from any question of reheating after deformation.

This paper was also discussed at the Additional Meeting held at Sheffield on May 15, 1929.

Mr. G. STANFIELD (Sheffield) said the subject-matter of the paper was of practical importance, because there were many structures where the imposition of heating to temperatures in the region of 250° to 300°C . on the cold-worked condition did occur, particularly, for example, in boiler work.

The theory put forward by Mr. Bolsover was very ingenious, and he (Mr. Stanfield) wished to mention one thing which rather supported it. Krivobok¹ had made some very interesting examinations of specimens cold-worked and then reheated to various temperatures; they showed that crystallisation along certain planes where local deformation had occurred did begin to take place at relatively low temperatures, something below 300°C . He believed that the lowest temperature actually used in those experiments was about 285°C ., which fitted in very well with the range which Mr. Bolsover had mentioned. Mr. Bolsover followed up that theory by suggesting that

¹ Paper read before the American Institute of Mining and Metallurgical Engineers, Feb. 1926.

after that temperature a condition of internal stress was left in the steel. There, he thought, the whole matter was very hypothetical. The recrystallisation apparently did begin to occur, but whether it was because that recrystallisation left a condition of internal stress that low impact values were obtained must be left for the present.

Dr. W. H. HATFIELD (Member of Council) asked, did the phenomenon investigated by Mr. Bolsover always happen? If not, why not? He suggested that quite a tonnage of that material was supplied in which the complaint with which Mr. Bolsover had had to deal had not turned up, when the variables, so far as he had them under control in the paper, were still under control. Would Mr. Bolsover say whether that were so or not, or whether his deduction No. 1 held. Was it not—he ventured to suggest that it was—within Mr. Bolsover's experience that other consignments of steel, submitted to exactly the same procedure, had not invariably behaved in such a brittle manner?

Mr. H. SUTTON (Farnborough, Hants.) asked whether in the author's experience different types of steel had shown any possible bearing on the problem of brittleness after tempering, in relation to the method of manufacture of the steel. He believed that a suggestion had been made by several workers in that field that the oxygen content of the steel might have some bearing on the matter. Brittleness of cold-rolled and tempered carbon steels had been of fairly general occurrence in his experience, and had given trouble on numerous occasions as a result of the reduced bending properties.

The CHAIRMAN (Professor C. H. Desch, F.R.S.) said Mr. Bolsover had made an important contribution to the knowledge of a remarkable phenomenon closely connected with blue-brittleness. It should be borne in mind that blue-brittleness was a characteristic of iron and its alloys which was not found in other metals, so that a theory which tried to account for those phenomena must be one that took into account the peculiar properties of iron at temperatures above atmospheric. He thought it would be interesting to know whether steels made by different processes did behave alike in that respect.

Mr. BOLSOVER, in reply, thanked the various members for their contributions to the discussion, and referred to the support given to his theory by the work of Krivobok, to which Mr. Stanfield had referred. That particular work had been very well done, and the changes of microstructure very neatly illustrated, and it certainly did appear to lend some confirmation to the theory of strain effects produced by sub-microscopic recrystallisation. Mr. Turner, at the London meeting, had similarly referred to work in connection with strain-etching figures, which followed very closely the phenomena dealt with in the paper.

In reply to Dr. Hatfield, he would say that in all the carbon steels

examined up to the present evidence of the brittleness in question had been found. That applied both to the solid and non-solid dead soft steel, and also to steels of higher carbon content. The question of alloy steels was only now receiving attention, but so far as it had gone, the work did seem to indicate that beneficial effects could be derived by the addition of nickel. That was not yet definitely established, as, apart from the fact that some nickel steels did show brittleness, it would be necessary to try out various combinations of stresses and temperatures of reheating, to mention only two factors, before one could say definitely that the influence of cold-work and reheating was not detrimental under any conditions.

Mr. Sutton had raised the important question of method of manufacture and oxygen content. It should be pointed out that the steel dealt with in the paper was a solid steel, deliberately chosen as such in order that no question of heterogeneity might enter into the test results. The author's experience was that with the other low-carbon steels, produced under Continental conditions, the brittleness referred to was certainly more marked than in English steels, including in the latter the normal rimming or effervescing type of dead soft steel. Whether that difference in behaviour was due to increase in oxygen content or not, he was unable to state.

Professor Desch had referred to the work in question as relating to blue-brittleness. Whilst it might be so described, it was hardly correct to speak generally of that type of brittleness under such a heading, as blue-brittleness covered a number of types, though in the author's opinion it was more correctly descriptive of that brittleness which occurred at a blueing heat—approximately 300° C. Again it should be emphasised that if a formed article, which had proved brittle due to the conditions dealt with in the paper, were cut up for examination, the parts which had not been deformed were perfectly ductile, and it was only the deformed areas which exhibited brittleness.

Mr. BOLSOVER wrote, in further reply: Most of the points raised in the discussion have already been dealt with in the verbal replies at London and Sheffield. Various members at the London meeting raised the question of the effect of added elements, and this has been partially dealt with in the reply to the Sheffield discussion. It is hoped that in course of time further data will be available relative to this aspect of the subject.

The instance of brittleness raised by Mr. Colbeck is of interest, in that the author would have anticipated that reheating to 330° C. would have dissipated to a considerable degree any brittleness induced by forming and reheating. It is possible that the type of forming was such as to require a slightly higher temperature than that found by the author to develop brittleness to the full degree, or it may be that commencement of failure actually occurred as the steel was being heated by the hot liquid, but only opened out into definite cracks

when the further heatings and coolings had produced such stresses as would lead to definite opening-up of the seams.

At the London meeting Mr. Allison, in his concluding remarks, dealt with the validity of the theory expounded, on the question of increased mobility with rise of temperature, and Mr. Whiteley could not fully accept the explanation of the 80° C. effect, as the samples after reheating to 250° C. would cool more or less slowly through this temperature range. Both these points are readily capable of explanation by the fact that the two effects dealt with as affected by a temperature of 80° C. (referred to in the paper) were tests carried out actually at that temperature, and were not simply reheatings followed by tests under ordinary atmospheric conditions.

The effect of thickness of strip in the galvanising operation is definitely of importance. In galvanising, except on very thin articles, the strip does not reach the temperature of the galvanising bath. In certain sizes, this results in the heating of the articles being galvanised to the ideal critical temperature for producing brittleness, whilst thinner articles will more nearly approach the temperature of the bath. If the thicker articles are left in the bath sufficiently long to reach the actual bath temperature brittleness does not occur, but the galvanising is ruined—a fact which is only too well appreciated by those dealing with such operations.

THE OXIDATION OF IRON AND STEEL AT HIGH TEMPERATURES.*

BY L. B. PFEIL, D.Sc., A.R.S.M. (SWANSEA).

INTRODUCTION.

IN industry the scaling of iron and steel at elevated temperatures is a matter of very great importance. During the reheating of steel ingots and the rolling of the metal into bars, sheet, and wire, an important percentage of the metal is converted into oxide. Besides being wasteful, this oxidation leads to defects which become of increasing importance when a product of good surface finish is demanded. In close annealing operations oxidation of the steel boxes occurs to a serious extent, and the cost of replacement forms an important item in the manufacturing costs of steel sheet and wire. In recent years there has been an increasing demand for steels possessing exceptional resistance to oxidation, and to meet this demand a large number of alloy steels have been introduced, which owe their resistance to oxidation mainly to the presence of nickel and chromium.

In view of the importance of oxidation at high temperatures, it is not surprising that a considerable number of papers bearing on the subject have been published in recent years. Stead,⁽¹⁾ Dickenson,⁽²⁾ McCormick,⁽³⁾ Pilling and Bedworth,⁽⁴⁾ Hatfield,⁽⁵⁾ and Smithells, Williams, and Avery,⁽⁶⁾ have investigated the formation of scale and the rate of oxidation. Other aspects of the iron-oxygen system have been dealt with by Sosman and Hostetter,⁽⁷⁾ Stead,⁽⁸⁾ and Tritton and Hanson,⁽⁹⁾ while information bearing on the subject is also to be found in papers dealing with the iron-oxygen-carbon and iron-oxygen-hydrogen systems.⁽¹⁰⁾ For a very complete series of references the "Bibliography of Metallic Corrosion" † should be consulted.

* Received January 5, 1929.

† Dr. W. H. N. Vernon. Edward Arnold: London, 1928.

The present paper deals with the mechanism of oxidation of iron and steel, and not with the rate of oxidation in a quantitative sense. The work was designed to elucidate the fundamental facts of oxidation, and to explain these facts on a common basis. The scope of the paper therefore covers a wide field both as regards the composition of the metal and the character of the oxidising medium. In industry the oxidation of iron and steel occurs very largely in an atmosphere consisting of carbon dioxide, steam, oxygen, and nitrogen, &c.—that is, the products of combustion of the fuels employed for heating purposes. Oxidation under such conditions differs in many respects from that obtained in the laboratory, so that it is improbable that the results and conclusions recorded will have an immediate and direct application to industrial problems. It is hoped, however, that the paper will serve a useful purpose by increasing knowledge, and so will lead eventually to results of practical value.

THE APPEARANCE, COMPOSITION, AND GENERAL PROPERTIES OF SCALE.

When iron and steel are oxidised at a red heat in air the scale does not form as a homogeneous deposit, but as a series of layers differing in appearance, properties, and chemical composition. This layer formation is produced whether the metal be pure iron, carbon steel, or alloy steel. Many brief references have been made in technical literature to this layer formation, but as this paper deals largely with the composition and formation of these layers, this feature will be described in detail. Scale in iron and ferrous alloys consists normally of three layers; they will be referred to throughout as :

Layer 1—the outside layer.

Layer 2—the middle layer.

Layer 3—the innermost layer in contact with the unoxidised metal core.

About 10 per cent. of the total scale thickness consists of the outside layer, about 50 per cent. of the middle layer, and 40 per cent. of the innermost layer. In Fig. 1 (Plate LVII.) are shown a number of severely oxidised pieces of metal from which the scale

has been removed in part so as to expose the various layers of scale and the unoxidised core. *A*, *B*, and *C* are plain carbon steels, *D* is a 2 per cent. silicon steel, *E* is a 2.75 per cent. nickel steel, and *F* a 5 per cent. tungsten steel. The specimens were set at an angle of about 30° to the vertical for the photograph, so that some idea of the thickness of the layers may be obtained. The numbers 1, 2, 3, and 4 represent layers 1, 2, and 3, and the unoxidised core respectively. The three carbon steels were originally $\frac{1}{2}$ in. in diam., the silicon steel $\frac{5}{8}$ in. in diam., the nickel steel $\frac{7}{16}$ in. square, and the tungsten steel was a disc 1 in. in diam. and $\frac{1}{2}$ in. thick. The degrees of oxidation of the specimens are not comparable, as the time of oxidation varied from three to seven days at a temperature of 1000° C. in air.

When oxidation has been severe it is possible to obtain samples of each layer almost free from contamination by the other layers, although it is seldom possible to separate the *whole* of each layer from the other layers and from the core.

It must not be supposed that three layers, and three layers only, are invariably present, for, while this is generally the case, it is often found that where disturbing influences have been at work the number of layers may be more or less than three. In particular, blistering of the scale affects the layer formation. Serious temperature fluctuations during the oxidation, and the presence of certain impurities in or on the metal may also spoil the three-layer deposit. These points will be elaborated later.

Appearance of Scale Layers.

Layer 1.—The outer surface of the outer layer of scale on iron has a smooth velvet-like appearance, while the under surface has a bright lightly-etched appearance. The thickness of the layer varies with the time and temperature of oxidation and with the air supply. The fracture of the layer is concoidal to crystalline, somewhat similar to black glass.

Layer 2.—The outer surface of the middle layer has a bright lightly-etched appearance, with a distinct indication of a crystalline structure. The inner surface shows perfectly in reverse all the details of the original surface of the iron before oxidation, such as identification numbers stamped on the iron, saw-marks,

and similar details. The position of the inner surface corresponds with that of the external dimensions of the iron before oxidation, and is therefore independent of the conditions of oxidation. The characteristics of the inner surface are very important from the point of view of any theory of oxidation, and are referred to again later. The fracture of layer 2 is, like that of layer 1, black and concoidal to crystalline, the outer half sometimes having a speckled appearance at high magnifications, the inner half being smooth.

Layer 3.—The outer surface of the innermost layer has a marked crystalline appearance. The layer consists of minute idiomorphic crystals, mainly almost perfect cubes, lightly fritted together, but becoming more consolidated where in contact with the metal core. The outer surface of the layer is so very porous that contact is only made with layer 2 at points, and thus the details of layers 2 and 3 are not conformable. The inner surface of layer 3 shows details corresponding with those on the surface of the unoxidised metallic core. The layer is very weak, and may be powdered between the fingers. Under the high-power microscope the crystalline aggregate is very beautiful, bearing a close similarity in appearance to bismuth specimens prepared by pouring off the mother liquor after partial solidification; the very high relief, however, makes ordinary photographic reproductions impossible. When the temperature of oxidation has been very high the minute cubic crystals are replaced by almost perfect spheres, indicating a partial melting of the crystals.

In Fig. 2 (Plate LVII.) the obverse and reverse of the three layers from the oxidised surface of an iron disc $\frac{3}{4}$ in. in diam. are shown. The outside layer was broken somewhat during removal so that only one-half is shown. The outer velvet-like surface and inner bright surface are clearly depicted. The inner surface of layer 2 shows the identification marks as perfectly as they were when stamped on the iron specimen; no sign of the marks is visible on the outer surface of the innermost layer, in spite of the fact that it was in contact with the inner surface of layer 2. This, as already pointed out, is due to the very loose nature of the innermost layer. Finally, the ill-defined character of the mark on the surface of the innermost layer which was in contact with the core will be observed. Naturally the identification marks on the metal were partly effaced by the oxidation, and the inner-

most scale layer was moulded to the final shape of the core. It is probable that the middle layer was moulded to the pattern of the metal at the moment when oxidation commenced, and hence is a much more perfect reproduction. The outside layer shows no sign of the identification marks. Experiment showed that three layers are present as soon as a sufficient thickness of scale has formed for microscopical examination to be practicable. Iron after heating at 1000°C. for 30 min. had a layer of scale about 0.004 in. thick, and the three layers could be detected in this deposit, but in thinner scales the layer formation could not be detected with certainty. Separation of the layers was not possible until much thicker deposits had been formed. The innermost layer could be separated from the other layers and from the core when the scale was 0.05 in. thick (4 hr. at 1000°C.), but the outer layer was not separable until the scale deposit was 0.147 in. thick (46 hr. at 1000°C.).

The details of the nature of the layers so far given refer to iron oxidised in air at temperatures between 750° and 1050°C. The remarks apply equally well to carbon steels oxidised under similar conditions, and with some reservations to alloy steels. The layer formation in the case of alloy steels will be discussed later. For the present it will suffice to say that the outer layer is often extensively cracked, and is generally more difficult to separate from the middle layer; the middle layer is similar to that exhibited by pure iron, while the innermost layer varies in character with the composition of the steel in question.

Composition of Scale Layers on Iron and Carbon Steel.

The three layers vary considerably in iron content, the outside layer being the lowest, and the innermost layer the highest in iron. Typical analyses of the three layers formed on pure iron oxidised at temperatures of 850°C. and 1050°C. , respectively, are given in Table I. The metal was originally 0.5 in. in diam., and the diameters before and after the removal of each layer are given, as well as the calculated proximate analysis.

The composition of the deposits is practically independent of the temperature of oxidation, and, although no figures in support are given in the table, it may be added that the composition

of the scale is also to a large extent independent of the time of oxidation.

It will be seen that the outer layer consists mainly of ferric oxide, the proportion of which is considerably in excess of that

TABLE I.—*Oxidation of Pure Iron.*

Layer.	Temperature of Oxidation. ° C.	Period of Oxidation. Days.	Limiting Diameters of Layers. In.	Iron. %	Proximate Analysis. %	
<i>Specimen A.</i>					FeO.	Fe ₂ O ₃ .
Layer 1	850	10	0.581 to 0.551	71.6	21.3	78.7
„ 2			0.551 „ 0.497	75.5	71.4	28.6
„ 3			0.497 „ 0.444	76.5	84.1	15.9
<i>Specimen B.</i>						
Layer 1	1050	9	0.635 to 0.589	71.55	20.6	79.4
„ 2			0.589 „ 0.498	75.45	70.7	29.3
„ 3			0.498 „ 0.380	76.0	77.8	22.2

present in magnetite (Fe₃O₄ contains 68.9 per cent. of Fe₂O₃ and 31.1 per cent. of FeO). The outer layer might therefore be looked upon as a mixture of magnetic oxide and ferric oxide, and on this basis it contains 68.7 per cent. of Fe₃O₄ and 31.3 per cent. of Fe₂O₃.

The middle layer is in a much lower state of oxidation, consisting of nearly three-quarters ferrous oxide and one-quarter ferric oxide, while the innermost layer is still richer in ferrous oxide. It is not suggested that any of the layers consisted of mixtures of definite chemical compounds of iron and oxygen; the considerations set out are only intended to convey an idea of the degree of oxidation in the layers. Nor is it suggested that each of the layers is uniform in composition; the analyses given are average figures for the whole of each layer. It is most probable that, just as the layers differ in composition, becoming richer in iron on passing inwards to the core, so also the individual layers vary in composition through their cross-section, becoming richer in iron also on passing inwards.

THE MECHANISM OF OXIDATION.

The formation of coherent scale deposits on iron is difficult to explain, owing to the absence of the disruptive action which

might be anticipated as a consequence of the expansion accompanying oxidation. The case considered in the following paragraphs is a specially difficult one to explain, and is selected for that reason, but the same reasoning might be applied to the oxidation of iron in any form except that of a large flat surface.

Consider the oxidation of a thick-walled iron tube, say, $\frac{1}{2}$ in. in diam. with a $\frac{3}{16}$ -in. bore. It may be shown experimentally that after a suitable period of oxidation (about 6 days at 900°C.) the bore of the tube becomes filled completely with scale, while at the same time a thick deposit of scale on the outside of the tube increases the external diameter to about 0.60 in. The scale on the outside of the tube consists of the three-layer formation already described, while the scale filling the bore consists of two portions. First, a *solid rod* of scale $\frac{3}{16}$ in. in diam.—that is, of the same diameter as the bore of the original tube—and, secondly, a loose deposit of lightly-adhering minute idiomorphic crystals filling the annular space between the rod of scale and the inner surface of the corroded tube. The central rod consists of a strong but brittle type of scale, with a fracture like that of black glass.

It is necessary to supply an explanation of how this scale formation developed. When the iron tube was first subjected to oxidation a thin-walled tube of scale 0.5 in. in diam. formed on the outside of the iron tube, and another tube of scale $\frac{3}{16}$ in. in diam. formed on the inside. Is it to be supposed that as oxidation proceeded the outer scale tube was gradually expanded by the pressure exerted by further scale forming beneath, until at last a diameter of 0.60 in. was reached? Is it to be supposed that the scale tube forming in the bore was compressed, until finally it ceased to be a tube at all—that is, until it became a solid rod? Such a mechanism would demand a pronounced degree of plasticity in the scale, since there is no sign of disintegration either in the final outer scale layer or in the rod forming the core. While it is possible that scale is plastic at very high temperatures, it is certain that at temperatures of the order of 1000°C. the scale behaves as a brittle and non-plastic substance. At still lower temperatures, such as 900°C. , it is exceedingly improbable that plastic deformation of the scale could occur to the extent in question. Even supposing for a moment that the scale were sufficiently plastic to undergo appreciable distortion without fracture, there remains the difficulty of accounting for the loose

scale in contact with the corroded metal, which, by reason of its porous nature, could not exert pressure. If this inner layer of scale had exerted a pressure on the outer portion of the scale it should itself be in a compact state, and not exist as a loose deposit with between 33 and 50 per cent. of voids.

This is not the only problem. Any explanation of the mechanism of oxidation must also explain how scale can form exhibiting a crystalline surface such as that recorded by Carpenter and Elam,⁽¹¹⁾ and also how it is possible for the outer layers of scale on alloy steels to be free from the alloying element. These two phenomena will be discussed at length later.

The suggestion that the progressive oxidation of iron involves the forcing of the already formed scale away from the metallic core by the pressure exerted by the new scale forming beneath is untenable, and a new explanation must be sought.

Mechanism of Oxygen Supply.—The two outer layers of scale on iron form as a dense deposit of a glass-like nature, and an explanation is required of how oxygen from the atmosphere passes through this scale so as to combine with the iron beneath, thus allowing oxidation to proceed. Oxygen *molecules* might diffuse along porous paths in the scale, such as cracks, but oxidation by this means would lead to irregular corrosion of the iron, for oxidation would occur most rapidly where the cracks were largest and most numerous. The smoothness of the core which is commonly found does not favour this mechanism, although if the cracks were of ultra-microscopic size the unevenness of corrosion might not be detected. However, oxidation occurring at the bottom of a crack or porous place would automatically seal the oxygen path and so bring oxidation by this mechanism to an end.

The alternative explanation is that the oxygen penetrates to the iron core with the aid of iron oxide as a "carrier." Thus one might picture oxygen dissolving in the scale and diffusing through to the core owing to the oxygen gradient. This appears to be the view held by Pilling and Bedworth.⁽⁴⁾ Another view, advanced by Whiteley,* is that ferric oxide is formed in the scale, and this is followed by a reaction between the ferric oxide and the iron core to form ferrous oxide. There is little, if any, difference between these two points of view. The probability is

* See discussion of Dickenson's paper.⁽²⁾

that there is a continuous series of solid solutions over the major portion of the iron-oxygen system from ferric oxide to ferrous oxide, with a gradually decreasing dissociation pressure on passing from the higher to the lower oxygen content. Thus, where the scale is in contact with the air the solution will be enriched in oxygen, but this enriched layer will not be in equilibrium with that beneath, so oxygen will pass inwards until it finally reaches the iron, with which it combines to form FeO . This question will be considered again after describing experiments illustrating the reactions which occur between scale and oxygen, between scales of different compositions, and between scale and iron.

Outline of New Hypothesis.

At the iron-scale interface, iron is continually being dissolved in the scale (that is, the iron is being converted into oxide, which then forms part of the scale deposit), forming an iron-rich solid solution, and diffusion of the iron occurs outwards through the scale to the scale-air interface. It is of little importance from the point of view of the hypothesis whether the iron dissolves and diffuses outwards as atoms of iron or as molecules of FeO ; the essential feature is that iron leaves the core without forcing outwards the already formed scale.

To give weight to the hypothesis it is necessary to show, first, that scale of higher oxygen content will react with scale of lower oxygen content; secondly, to show that metallic iron is oxidised by oxygen-rich scale; and, thirdly, that iron passes outwards through the scale to the surface. In the following sections an attempt will be made to establish these three points.

The Reactions between Scale and Oxygen, between Scales of Different Compositions, and between Scale and Iron.

Reactions between Scale and Oxygen.—The only oxide of iron which is stable when heated in air to temperatures of the order of 800° to 1100° C. is ferric oxide. At very high temperatures the dissociation pressure of ferric oxide is greater than the oxygen pressure of the atmosphere (152 mm.), and partial decomposition sets in. The composition of the stable oxide over about 1200° C.

lies between Fe_2O_3 and Fe_3O_4 , being nearer Fe_3O_4 when the temperature is higher. The following analyses will serve to show the effect of heating scale in air for 2 hr. at 900°C . :

	Fe%.	O%.
Scale from electrolytic iron	71.80	28.20
Scale after heating in air	69.93	30.07
Pure ferric oxide	69.94	30.06

Reactions between Scales of Different Compositions.—Weighed samples of scale of known composition in two alumina-lined fused-silica boats were placed together in an electrically heated fused-silica tube-furnace and heated either in pure nitrogen or *in vacuo*. After heating, the scale samples were again weighed, and were then analysed for their iron contents. In different experiments changes were made in the relative quantities and compositions of the two scales, and in the time of heating and temperature. Results of experiments are given below :

No. 1.—Scales Heated at 950°C . in Nitrogen.

	Scale A.	Scale B.
Original iron content	77.75%	70.05%
Original weight of scale	2.3106 grm.	4.9244 grm.
After 20 hr. heating	2.4028	4.8312
Change in weight during 20 hr. . . .	+ 0.0919	— 0.0932
After further 48 hr. heating	2.4782	4.7549
Change during further 48 hr. . . .	+ 0.0754	— 0.0763
After second period of 48 hr. . . .	2.4794	4.7542
Change during second 48 hr. . . .	+ 0.0012	— 0.0007
Final iron content by analysis	72.65%	72.60%
Final iron content by calculation from original composition and change in weight	72.5%	72.5%

From these figures it will be seen that a scale approximating to the composition FeO reacts with a scale of the composition Fe_2O_3 until eventually both scales have the same composition. The loss in weight of one scale (high in oxygen) corresponds with the gain in weight of the other (poor in oxygen). The final composition, calculated on the assumption that the change in weight is due to the passage of oxygen from one scale to the other, corresponds very well with the final composition by analysis.

The reaction had proceeded just over half-way after 20 hr., and was practically complete after 68 hr. This appears to indicate that the reaction is a very slow one. It must be borne in mind, however, that in the furnace the two samples of scale were separated by a distance of about 3 in., and that the oxygen

evolved by the dissociation of the one scale had to diffuse through this distance in a nitrogen atmosphere before it could combine with the other scale. The reaction would obviously be much faster if the diffusion path were shorter, and, indeed, this was found to be the case. It is probable that, were the two scales actually in contact, the reaction would be very rapid.

No. 2.—Scales Heated at 950° C. for 96 hr. in Nitrogen.

	Scale A.	Scale B.
Original iron content	76·95%	70·05%
Original weight	13·2336 grm.	1·5246 grm.
Weight after 96 hr. heating	13·3642 „	1·3971 „
Change in weight	+ 0·1306 „	— 0·1275 „
Final iron content by analysis	76·25%	76·40%
Final iron content by calculation	76·20%	76·50%

In this case also the reaction proceeded until both scales had the same composition, but the use of a large proportion of the iron-rich scale *A* led to equilibrium at a much higher iron content.

These two examples are sufficient to indicate what has been definitely proved by a large number of experiments not recorded—namely, that *when the average iron contents of the two samples of scale are in excess of 72 per cent., exchange of oxygen continues until both samples have the same analysis.*

No. 3.—Scales Heated at 950° C. in Nitrogen.

	Scale A.	Scale B.
Original iron content	76·03%	70·05%
Original weight	2·6114 grm.	14·2363 grm.
Weight after first heating of 41 hr.	2·7159 „	14·1312 „
Change during first heating	+ 0·1045 „	— 0·1051 „
Weight after second heating of 48 hr.	2·7408 „	14·1103 „
Change during second heating	+ 0·0249 „	— 0·0209 „
Weight after third heating of 48 hr.	2·7453 „	14·1070 „
Change during third heating	+ 0·0045 „	— 0·0033 „
Weight after fourth heating of 48 hr.	2·7474 „	14·1041 „
Change during fourth heating	+ 0·0021 „	— 0·0029 „
Total change in weight during 185 hr. at 950° C.	+ 0·1360 „	— 0·1322 „
Final iron content by analysis	71·9%	70·60%
Final iron content by calculation	72·15%	70·65%

From this experiment it will be seen that when a relatively large proportion of the oxygen-rich scale is employed, the reaction proceeds rapidly at first, but ceases before the two scales reach the same composition. From this experiment it *appears* that

scale containing 72 per cent. of iron is in equilibrium with any scale of lower iron content. Several further examples of this "incomplete" reaction follow.

No. 4.—Large Amount of Low-Iron Scale and Small Amount of Medium-Iron Scale Heated for 96 hr. at 1000° C. in vacuo.

	Scale A.	Scale B.
Original iron content	72.06%	70.20%
Original weight	1.7339 grm.	12.2072 grm.
Weight after 96 hr. heating	1.7348 "	12.2022 "
Change in weight	+ 0.0009 "	— 0.0050 "
Final iron content by analysis	71.96%	70.26%
Final iron content by calculation	72.06%	70.40%

These figures show that, in spite of the higher temperature and the heating *in vacuo* instead of in nitrogen, there is still no reaction between scale containing 72 per cent. of iron and scale richer in oxygen.

No. 5.—Large Amount of Low-Iron Scale Heated with Small Amount of High-Iron Scale for 23 hr. at 1200° C. in vacuo.

	Scale A.	Scale B.
Original iron content	77.10%	70.00%
Original weight	1.5011 grm.	16.0806 grm.
Weight after 3 hr. heating	1.6053 "	15.9725 "
Change in weight	+ 0.1042 "	— 0.1081 "
Weight after second period of 20 hr. heating	1.6090 "	15.9683 "
Change in weight during second heating	+ 0.0037 "	— 0.0042 "
Final iron content by analysis	71.94%	70.58%
Final iron content by calculation	71.9%	70.55%

A still higher temperature was employed to determine if there were any difference in the equilibrium position at different temperatures. The high-iron scale was oxidised again to 72 per cent. of iron, the great majority of the change occurring during the first 3 hr.

From these experimental results it follows that there must be a continuous series of solid solutions from 72 per cent. of iron and 28 per cent. of oxygen to ferrous oxide (77.73 per cent. of iron and 22.27 per cent. of oxygen). That this must be the case is readily demonstrated, for if it be assumed that no intermediate phase between Fe_3O_4 and FeO can exist, then intermediate compositions must consist of mechanical mixtures of Fe_3O_4 and FeO . The dissociation pressure of a mixture of the two oxides would be that of the higher oxide, Fe_3O_4 , and if the

oxygen pressure were less than the dissociation pressure of Fe_3O_4 , the latter would be unstable, and the reaction $3\text{FeO} + \text{O} = \text{Fe}_3\text{O}_4$ could not occur. Oxygen, therefore, could not pass from one scale to the other if both were at the same temperature and pressure. For the reactions to occur the dissociation pressure over the composition range in question must vary continuously, and this could only be the case if the range were occupied by a solid solution series.

The fact that scale containing 72 per cent. of iron will not react with scale of a lower iron content may be interpreted as being due to the presence of a second solid solution in oxide containing less than 72 per cent. of iron. Ferric oxide (69.94 per cent. of iron) crystallises in the hexagonal system, while magnetite and ferrous oxide crystallise in the cubic system. Sosman and Hostetter⁽⁷⁾ have deduced from their results that a continuous solid solution series exists from Fe_2O_3 over to a point near Fe_3O_4 , while the present work indicates a continuous solid solution series from FeO to a point beyond Fe_3O_4 . It is safe to assume that the oxygen-rich solid solution is hexagonal, and the iron-rich solution cubic. There must be a range of composition over which both phases are present, and in this range the dissociation pressure will be constant. The experimental evidence set out in this paper indicates that the upper limit of the two-phase area is at 72 per cent. of iron, which is equivalent to 73.5 per cent. of Fe_2O_3 and 26.5 per cent. of FeO . Smits and Bijvoet⁽¹⁰⁾ have considered the system Fe_2O_3 - Fe_3O_4 , and find that, on theoretical grounds, it is improbable that the solid solution series is continuous.

The Reactions between Scale and Iron.—Experiments were carried out in two ways. First, an alumina-lined boat was filled with a weighed and analysed quantity of pure iron oxide (scale from electrolytic iron), and a weighed strip of electrolytic iron sheet was placed on the top of the scale. A prolonged heating of the charged boat *in vacuo* followed. Secondly, an alumina-lined silica boat was filled almost flush with the top with a weighed and analysed quantity of pure scale, and a weighed piece of electrolytic iron sheet was placed on the top of the boat so as to be very near to but not touching the scale. In this case also a prolonged heating *in vacuo* followed.

In both cases the electrolytic iron was heated for several days

in vacuo before the experiment in order to remove all occluded gases. Great care was taken also to avoid the contamination of the vacuum by oxidising and reducing gases.

Two examples are given, in both of which the heating was carried out at 1000°C . for five days. In the first example, the scale and iron were in contact, and in the second they were separated by a space of about 1 mm. In the first case, the scale was separated after the experiment into two layers, the upper portion, *A*, which was in contact with the iron strip, and the lower half, *B*. Each portion was weighed and analysed, and the cleaned iron strip was also weighed. In the second case, the scale was weighed and analysed after heating, the scale which had formed on the iron was separated, weighed, and analysed, and the cleaned strip was weighed.

*Electrolytic Iron and Scale from Electrolytic Iron Heated in Contact
for 120 hr. at 1000°C .*

Scale.		Iron.	
Original iron content of scale	73.48%		
Original weight	9.4576 grm.	Original weight	6.4574 grm.
Final weight of portion <i>A</i> .	6.0315 "	Final weight	4.8756 "
Final weight of portion <i>B</i> .	5.0070 "	Decrease in weight . .	1.5818 "
Total weight after heating .	11.0385 "		
Increase in weight	1.5809 "		
Final iron content of portion <i>A</i>	77.30%		
Final iron content of portion <i>B</i>	77.30%		

The average iron content of the scale after the experiment was 77.3 per cent., which is a close approach to the iron content of FeO (77.73 per cent. Fe).⁽¹³⁾ The increase in the iron content of the scale might have occurred in one or both of two ways. Iron from the strip might have dissolved in the scale, followed by the diffusion of the iron downwards through the scale, the process continuing until a homogeneous solid solution saturated with iron was produced. On the other hand, the increase might have resulted owing to the dissociation pressure of the scale being greater than that of the iron saturated with FeO ; as a consequence, oxygen would pass from the scale particles into the furnace atmosphere, whence it would be withdrawn by the iron to form new scale having, of necessity, a higher iron content and lower dissociation pressure than that from which the oxygen was

derived. The experiment which follows indicates more definitely the mechanism in operation, for in this case, there being no contact between the scale and the iron, direct solution of the iron in the scale could not occur.

Electrolytic Iron and Scale Heated out of Contact for 120 hr. at 1000° C.

Scale.		Iron.	
Original iron content	. 73.48%	Original weight	. 6.5442 gm.
Original weight	. 7.9536 gm.	Weight of iron plus new scale	. 6.9333 "
Final weight	. 7.5654 "	Increase in weight	. 0.3891 "
Decrease in weight	. 0.3882 "	Final weight of cleaned iron	. 5.2203 "
Final iron content	. 77.24%	Decrease in weight of iron	. 1.3239 "
Final iron content by calculation	. 77.30%	Weight of new scale on iron	. 1.7130 "
		Iron content of new scale on iron	. 77.28%

These figures show that, in spite of the lack of contact between the scale and iron, a reaction had occurred, the scale having suffered a loss in weight and the iron an equal gain in weight. It is clear that during the heating oxygen passed from the scale to the iron, as a result of which the scale contained a much higher percentage of iron after the experiment, and new scale was formed on the iron. It is of interest to note that the final analyses of the oxides in this experiment (77.24 and 77.28 per cent. of iron) are almost identical with those obtained in the previous experiment where the scale and iron were in contact.

From these two experiments it follows that, whereas an increased iron concentration in scale *may* be possible by direct solution of iron, it *certainly can occur without* direct solution of iron in the scale.

It is improbable that equilibrium conditions were completely attained in these two experiments. Longer periods of heating resulted in somewhat greater percentages of iron in the oxide, but serious difficulties were encountered when very long times of heating were attempted, and the results, being unreliable, are not included.

THE CAUSE OF THE LAYER FORMATION IN SCALE DEPOSITS.

It is now possible to discuss with more certainty the cause of the three-layer formation in scale, and to review the suggested

mechanism of oxidation in the light of the preceding experimental results.

Dealing first with the outside layer, the composition of which has been found to vary from 71.04 to 71.86 per cent. of iron, it is noteworthy that the analysis of this layer always shows an iron content lower than the lower limit found for the iron-rich solid solution (72.0 per cent. of iron). This suggests at once that the outer layer is caused by the presence of the second phase—a suggestion which appears to fit in with the known facts. The layer increases in thickness as the oxidation is continued; it also increases in thickness when the oxidising conditions are more severe, and disappears entirely when the atmosphere is only weakly oxidising.

The molecules of which this layer is composed are ever changing, for iron is continually being brought to the surface by diffusion, thus tending to thicken the layer; at the same time the thickening tends to reduce the rate at which oxygen reaches the inner part of the layer, and the inner portion, becoming enriched in iron, reverts to the cubic phase and joins layer 2.

The experimental work so far carried out does not permit of a definite statement as to whether the division between layers 1 and 2 is caused by the disappearance of the low-iron phase or by that of the high-iron phase. That it is one of the two is extremely probable, but an investigation with the aid of X-rays is certainly called for to settle this point.

Considerable attention has already been directed to the division between layers 2 and 3. It has already been pointed out that the inner face of layer 2 corresponds both in position and in surface characteristics with the surface of the unoxidised iron. This is true, whatever the conditions of oxidation.

When iron is oxidised, the scale grows both outwards and inwards from a position determined by the original dimensions of the iron. The scale found outside the original dimensions of the iron reaches its position by diffusion; that found within the original dimensions of the iron remains there after formation only because if it diffused outwards contact would be lost between the outer scale layers and the core. If this were to happen, no further supplies of iron could reach the outer layers until contact was made again. By expanding this point an explanation is

available why the innermost portion of the scale is so very porous in character. It is suggested that the natural velocity of diffusion of the iron outwards through the scale is greater than the rate of oxidation of the iron core ; hence there is a tendency for contact to be lost between the scale and the core, and only just so much oxide remains in layer 3 as is necessary to maintain a diffusion column of sufficient cross-section to carry outwards the iron which is oxidised. These diffusive columns, built up of minute idiomorphic scale crystals and joining the core to the middle scale layer, must be pictured as ever changing, new columns growing from time to time like stalagmites from the core, accompanied by the absorption of other columns by the outer compact scale layers.

It is now clear why the inner surface of the middle layer reproduces the surface characteristics of the original iron, for it was formed at the very inception of oxidation, and the first formed scale would of necessity follow the surface inequalities of the iron. The surface characteristics of the iron are not visible on the outside surface of the middle layer, because the deposition of oxide on the outer surface gradually obliterates the markings. Similarly, no markings are visible on either surface of the outside layer. The outer surface of the innermost layer is too porous to show clearly defined details, although it was in contact with the inner surface of the middle layer on which the markings were most clearly defined.

Reverting to the suggestion that the diffusion of iron outwards through the scale would, if possible, occur at a greater rate than the production of oxide at the core, several important points remain to be considered. If the rate of oxide production were the greater, there would be an accumulation of oxide at the core, which would exert a disrupting pressure on the outer layers of the core and cause a cracked and disintegrated scale deposit. If, on the other hand, diffusion outwards continued for a prolonged period, under some exceptional circumstances, at a greater rate than that at which oxide was produced, a hollow space would form between the scale and the inner core. It is difficult to see why the rate of diffusion should normally be exactly equal to the rate of oxide production except on the basis already suggested, that the rate of diffusion outwards is controlled by the cross-

section of the diffusive path, which in turn is determined by the rate of oxidation of the metallic core. It might be supposed that oxidation would cease if contact were lost between the core and the outer scale layers, for it is almost certain that the oxygen reaches the core by diffusion as one component of the solid solution of which the scale is composed. This, however, would not be the case, for although oxygen could no longer diffuse inwards in solution it could still bridge the gap in the gaseous state, since the enclosing scale envelope would have an appreciable dissociation pressure. Thus, if contact were lost between scale and core it would be re-made after an interval owing to the expansion accompanying the slow accumulation of oxide at the core. It is, indeed, possible to conceive of diffusion of the iron outwards taking place intermittently, the innermost scale layer being rapidly removed by diffusion, followed by a period during which contact is again built up between the outer scale and the core—contact when completed being immediately followed by rapid diffusion and removal once again of the innermost layer.

That these considerations approach the truth is indicated by the fact that a suitable adjustment of the conditions makes it possible to obtain both the disintegrated scales which might correspond with the case where the rate of oxidation exceeded the rate of diffusion, and the hollow scale corresponding with the reverse case.

Disintegrated Scale.—Disintegrated scale may be produced by the presence of certain elements in the iron, or more conveniently by coating the iron with a thin layer of some compound of lead before the oxidation. A wash made from litharge and water is convenient. The litharge melts at about 877°C ., so that a uniform thin coating remains on the iron when it has been heated above this temperature. Three pieces of severely oxidised $\frac{1}{2}$ in. diam. iron are shown in plan and elevation in Fig. 3, *A*, *B*, and *C* (Plate LVIII.). Pieces *A* and *C* had received the lead wash, while *B* had not. The three pieces were oxidised under identical conditions for 96 hr. at 1000°C . The piece *B* had the characteristic smooth scale surface with the ends well rounded, but the scale on *A* and *C* was severely cracked and disintegrated, particularly at the ends. The dimensions of the unoxidised cores showed that the lead had not caused any important increase in

the rate of oxidation, the smaller diameter of the oxidised piece *B* being due to the more compact nature of its scale. It is considered that the swollen nature of the scale on pieces *A* and *C* was due to the lead in the scale having caused a decrease in the rate of diffusion of the iron outwards, so that oxide, accumulating at the core, forced outwards the already formed scale, with a consequent cracking of the non-plastic deposit.

Hollow Scale or Loose Core Type.—In Fig. 4 (Plate LVIII.) is shown an example of this type of deposit. Three pieces of $\frac{1}{2}$ in. diam. iron were placed in a fireclay boat at an angle of about 30° to the horizontal, and were oxidised in air for three days at a good red heat. (The temperature was not measured.) The three pieces, two with the scale intact, are shown in elevation at *A*, while the three iron cores removed from the scale shells are shown in corresponding positions at *B*. At *C* a section through the scale with the core still in place is shown, and at *D* a scale shell is shown together with the corresponding metallic core. Finally, one of the pieces with the scale broken away to expose the core is shown in plan at *E*.

The iron cores had a diameter of 0.42 in., and the inside diameter of the scale was 0.48 in., so that the clearance between the cores and the scale shells was 0.03 in. The shell of scale consisted of one layer only, with a columnar fracture clearly visible in Fig. 4, *C* and *D*, suggesting oxide crystals growing at right angles to the surface and passing right through the deposit. The cross-section of the scale tubes showed porous spots like blowholes, which were accompanied by protuberances on the outside surface; this feature is also prominent in Fig. 4, *C* and *D*. The average analysis of the scale showed 73.95 per cent. of iron. The iron cores had a thin coating of scale about 0.005 in. thick in contact with them, which may be seen partly broken away in Fig. 4, *B*.

The above specimens were produced accidentally under rather doubtful conditions, particularly as regards temperature, and efforts have been made to reproduce the structure under exact conditions. Several other examples of this type of scaling have been obtained, but none exhibiting so great a clearance as that shown in Fig. 4, and it is not yet possible to make a very definite statement as to the best conditions of development.

The composition of the iron is important, electrolytic iron giving the hollow scale under widely varying conditions (time, temperature, and atmosphere), and much more frequently than any other form of iron.* The presence of gas in the electrolytic iron does not appear to be a factor of importance. Experiments carried out with decarburised steel, oxidised first just below Ac_3 and followed by a short heating just over Ac_3 , have given interesting results, leading to the suggestion that the sudden contraction of the core on passing through the change point breaks the contact between scale and core, causing a decrease in the rate of oxidation, but no decrease in the rate of diffusion.

Some evidence has also been obtained showing that the hollow deposit has only a temporary existence, the annular space being filled again with scale if oxidation is continued.

It is regretted that the explanation of this very remarkable structure must be left for the present without any very definite proof. The diffusion explanation does, however, appear to fit in with such facts as are at present known very much better than explanations based on the complicated properties of unknown iron-bearing vapours. It may be added that the change in density during the oxidation of FeO into Fe_2O_3 would not produce an expansion sufficient to give the clearance between the scale and core shown in Fig. 4.†

THE ENVELOPMENT OF FOREIGN PARTICLES BY PROGRESSIVE OXIDATION.

In this section important experimental results are described which throw light on the manner in which scale deposits are built up by progressive oxidation. It had frequently been noticed that small particles of foreign matter (such as pieces of muffle) falling on the surface of oxidising iron were gradually buried. The scale grew up round these particles until they finally disappeared beneath the surface, but they could afterwards be found by breaking up the layer of scale. From such observations it was deduced that if the iron were coated with some porous but

* See Pilling and Bedworth (4) (*loc. cit.*, p. 566).

† FeO (77.73 per cent. Fe): density from lattice, 5.9; actual determination in scale containing 75.8 per cent. iron, 5.56. Fe_2O_3 (69.94 per cent. Fe): density from lattice, 5.25; actual determination in scale of corresponding composition, 5.25.

non-reactive substance the scale would pass between the particles, finally burying them but leaving their position unchanged.

If it could be shown beyond all doubt that the particles remained unmoved and were buried beneath a layer of scale and at the same time separated from the iron core by a layer of scale, it would be complete proof that the mechanism of oxidation was not a simple forcing away of the scale already produced by the expansion accompanying the formation of further scale.

A suitable substance for coating or painting the iron was found in a distemper of green chromium oxide and water. After painting the iron with this substance and then subjecting it to prolonged oxidation, the scale was separated into layers. In this experiment four layers were obtained, the innermost being divided into two portions. The samples were analysed for chromium, and the results obtained in two separate experiments were as follows :

Number of Layer.	Approximate Diameter of Layers. In.	Chromium.	
		Experiment 1.—Thin Coat of Cr_2O_3 . %	Experiment 2.—Thick Coat of Cr_2O_3 . %
1. Outside layer	0.65 to 0.60	0.032	0.077
2. Middle layer	0.60 „ 0.50	0.030	0.960
3. Inner layer {	A. Outer portion	0.230	0.650
	B. Inner portion	0.037	0.073
	0.50 „ 0.40		
	0.40 „ 0.35 (core)		

The results indicate very clearly that the chromium oxide coating did not remain on the surface but became buried beneath the scale. The probability is that the chromium coating lay between layers 2 and 3A, that is, as a tube 0.5 in. in diam., which was the original size of the iron. In one of the experiments the chromium layer was included in the layer 3A, and in the other in the layer 2. The small amounts of chromium found in the other layers may be accounted for by contamination of one layer with another during separation.

Microscopic examination of the scale deposits in cross-section revealed a dull black discontinuous ring approximately in the centre of the ring of scale, and since this dull band was never present unless painting had been resorted to, it may be taken as

confirming the position of the Cr_2O_3 as determined by the analytical results.

As there is the possibility that the chromium oxide paint behaved as something more than a perforated septum through which the scale passed, the experiment was repeated using nickel oxide as the paint. The results were as follows :

Layer No.		Dimensions of Layer. In.		Nickel. %
1.	Outside . . .	0.62	to 0.57	Trace
2.	Middle . . .	0.57	„ 0.50	0.48
3A.	Inner . . .	0.50	„ 0.47	7.08
3B.	Innermost . . .	0.47	„ 0.43	Trace

In this case not only were the analytical results most conclusive, but the examination of the scale deposit showed a layer of *metallic* nickel within the scale. The nickel deposit was between the layers 2 and 3A, and hence occupied the position in which it was originally placed. The nickel layer was not continuous, but, like the chromium oxide layer, consisted of small pieces such as might result if the original paint had disintegrated somewhat owing to contraction on heating.

Similar experiments to those just described have also been carried out under slightly different conditions. The iron was subjected to oxidation for a few days first, and the paint was then put on to the outside surface of the scale. A second period of heating followed, during which further oxidation occurred. After the second oxidation the scale was separated into layers, and the latter were analysed. Results again showed that iron oxide passed through the paint layer, so that after prolonged oxidation the nickel or chromium was found as a layer deep-set in the scale deposit.

These experiments show conclusively that as oxidation proceeds the first formed scale is not forced outwards by the expansion accompanying the formation of further scale, but that in some way the *newly formed scale is deposited on the outside surface of the previously formed scale.*

THE OXIDATION OF ALLOY STEELS.

A study of the scale layers produced when alloy steels are oxidised supplies invaluable information relating to the mechanism

of oxidation of ferrous metals in general, as well as throwing light on the problem of heat-resisting special steels.

The time required to produce a given thickness of scale on the alloy steels is, in general, greater than for the carbon steels. In almost every case, however, the scale deposit consists of three separable layers. The outer layer is not nearly so readily separated from the middle layer as in the case of the carbon steels, but the innermost layer may in all cases be separated perfectly and with great ease from the middle layer.

Steels of the following compositions have been studied :

Type of Steel.	Period of Oxidation. Days.	Analysis.
1. Nickel steel . . .	6	Ni 2·75, C 0·36, Mn 0·54, Si 0·21, S 0·039, P 0·031 per cent.
2. Nickel-iron alloy . .	13	Ni 36·0 per cent.
3. Stainless steel . . .	6	Cr 12·23 per cent.
4. Nickel-chromium steel .	6	Cr 0·85, Ni 3·18, C 0·32 per cent.
5. Tungsten steel . . .	6	W 5·5, C 0·7 per cent.
6. Vanadium steel . . .	7	V 0·27, C 0·56 per cent.
7. Manganese steel . . .	4	Mn 3·07, C 0·9 per cent.
8. Silicon steel . . .	4	Si 2·02 per cent.

Suitable pieces of these steels were heated in an electric muffle furnace at 1000° C. with free access of air for convenient lengths of time to give heavy deposits of scale. In each case the scale was separated into three layers according to the natural laminations. Some contamination of the layers was inevitable, but this was not sufficiently serious in any experiment to make it difficult to draw definite conclusions as to the composition of the layers. The layers were analysed for the alloying element and for total iron. The results are collected in Table II.

It will be seen that in all cases except that of manganese steel, the two outer scale layers contain only very small amounts of the alloying element as compared either with the original steel or with layer 3. Layer 3, on the other hand, contains about twice as much alloying element as the original steel. This point is brought out best in the column showing the ratio of iron to alloying element in the original steel and in the three corresponding layers of scale.

TABLE II.—*Alloy Steels—Analyses of Scale Layers.*

Material.	Alloy Element. %	Iron. %	Ratio of Iron to Alloy.	Probable Proximate Analysis.			
				Iron Oxide. %	Im- purities. %	Other Constituents. %	Total. %
Nickel steel.							
Original steel	2.75 Ni	96.06	35.0	...	...	...	...
Layer 1	Nil	71.24	∞	99.5	1.2	Nil	100.7
" 2	0.16 Ni	74.78	467.0	99.0	1.2	0.16 Ni	100.2
" 3	7.07 Ni	69.72	9.8	91.7	1.2	7.07 Ni	99.97
Nickel-iron alloy.							
Original alloy	36.0 Ni	64.0	1.78	...	...	...	...
Layer 1	1.46 Ni	69.64	47.7	97.4	...	1.46 Ni	98.86
" 2	2.29 Ni	68.44	29.8	90.7	...	2.29 Ni	92.99
" 3	52.08 Ni	39.14	0.75	51.5	...	52.08 Ni	103.58
Stainless steel.							
Original steel	12.23 Cr	86.5	7.08	...	...	...	...
Layer 1	0.61 Cr	70.1	115.0	98.0	0.8	0.89 Cr ₂ O ₃	99.69
" 2	1.12 Cr	68.16	60.8	90.5	0.8	1.64 Cr ₂ O ₃	92.94
" 3	23.32 Cr	48.04	2.06	63.2	0.8	34.1 Cr ₂ O ₃	98.1
Nickel-chromium steel.							
Original steel	{ 3.18 Ni 0.85 Cr }	94.8	{ 29.8 111.5 }	...	...	...	...
Layer 1	{ 0.48 Ni 0.14 Cr }	70.9	{ 148.0 505.0 }	99.1	1.0	{ 0.48 Ni 0.20 Cr ₂ O ₃ }	100.78
Layer 2	{ 0.64 Ni 0.18 Cr }	74.0	{ 115.0 411.0 }	98.1	1.0	{ 0.64 Ni 0.26 Cr ₂ O ₃ }	100.0
Layer 3	{ 8.37 Ni 1.80 Cr }	67.3	{ 8.05 37.4 }	88.5	1.0	{ 8.37 Ni 2.63 Cr ₂ O ₃ }	100.5
Tungsten steel.							
Original steel	5.50 W	92.7	16.9	...	...	...	...
Layer 1	0.67 W	69.0	103.0	96.5	1.8	0.85 WO ₃	99.15
" 2	5.55 W	66.9	12.0	88.7	1.8	7.0 WO ₃	97.5
" 3	9.67 W	65.34	6.75	86.0	1.8	12.2 WO ₃	100.0
Vanadium steel.							
Original steel	0.27 V	98.5	365.0	...	...	...	...
Layer 1	0.08 V	69.92	873.0	Insufficient vanadium present to allow reliable deductions			
" 2	0.16 V	72.92	455.0				
" 3	0.40 V	75.92	190.0				
Manganese steel.							
Original steel	3.07 Mn	96.0	31.1	...	...	...	...
Layer 1	1.53 Mn	69.54	45.6	97.2	0.5	2.22 Mn ₃ O ₄	99.92
" 2	2.58 Mn	72.70	28.4	96.4	0.5	3.74 Mn ₃ O ₄	100.64
" 3	2.50 Mn	73.40	29.4	96.6	0.5	3.62 Mn ₃ O ₄	99.72
0.71% manganese steel.							
Original steel	0.708 Mn	99.2	140.0	...	...	...	...
Layer 1	0.282 Mn	71.3	253.0	...	...	...	...
" 2	0.673 Mn	74.7	111.0	...	...	...	...
" 3	0.590 Mn	75.6	128.0	...	...	...	...
Silicon steel.							
Original steel	2.02 Si	97.6	48.3	...	...	...	...
Layer 1	Trace	71.62	∞	100.0	...	...	100.0
" 2	"	74.3	∞	98.5	...	...	98.5
" 3	4.38 Si	68.32	15.6	89.9	...	9.39 SiO ₂	99.29

In the last column of the table is given the probable proximate analysis of the scale layers. This analysis is based on the assumption that the iron is present in the scale in the same state of oxidation as it would be in the equivalent layer of a pure iron scale. An allowance has been made for impurities such as manganese, silicon, &c., and the balance thus consists of the alloying element and/or its oxide.

Before discussing the results in detail, attention must be drawn to the fact that measurements showed that, as in the cases of plain carbon steels and pure iron, the outside dimensions of the innermost scale layer from alloy steels corresponded with the dimensions of the unoxidised steel. This point is of great importance in connection with the explanation of the mechanism of oxidation.

(1) *Nickel Steel*.—The results for nickel steel showed a complete absence of nickel in the outer layer, which formed about one-seventh of the whole scale deposit. The middle layer contained little more than traces of nickel, and formed over one-half of the total scale. The innermost layer contained $2\frac{1}{2}$ times as much nickel as the original steel, or, expressed as an iron to nickel ratio, $3\frac{1}{2}$ times as much nickel as the original steel.

Under the microscope the cross-section of the scale showed very important differences from scale derived from iron or from plain carbon steels. First, the inner layer contained minute metallic particles embedded in the oxide. Secondly, intercrystalline penetration into the metallic core was more pronounced. Thirdly, beyond the range of intercrystalline oxidation of the core an altered zone could be seen in the metal. In this zone an enormous number of extremely minute specks, probably of iron oxide, could be seen.

(2) *Nickel-Iron Alloy*.—Comparatively small amounts of nickel were found in the two outer layers, but a remarkable enrichment of nickel was found in the innermost layer. The nickel was in the metallic form, possibly containing small amounts of metallic iron in solution. Under the microscope the oxide in layer 3 appeared in a vermicular form leading from the unaltered core outwards. The layer was so rich in metallic nickel as to be almost malleable, and could be removed from the unaltered core only with difficulty. Intercrystalline penetration was marked, as was also the altered zone referred to in the 2.75 per cent. nickel steel.

(3) *Stainless Steel*.—Relative to the iron content, the inner scale layer contained $3\frac{1}{2}$ times as much chromium as the original steel, while the two outer layers contained only a fraction of it. The chromium was present in the scale as oxide, giving to the innermost layer a greenish tinge and making solution of this layer for analysis possible only with the aid of a sodium peroxide fusion.

(4) *Nickel-Chromium Steel*.—The two outer layers contained less than one-tenth of the nickel and chromium present in the innermost layer, while the latter contained, relative to the iron, three times as much nickel and chromium as the original steel. It is of interest to note that the ratio of nickel to chromium in the original steel and the three scale layers was not constant; the ratios were: original steel, 3.74; layer 1, 3.4; layer 2, 3.6; layer 3, 4.65. This showed that the presence of small quantities of nickel and chromium in the outer scale layers was not due simply to contamination with layer 3 during separation.

(5) *Tungsten Steel*.—Whereas little tungsten was present in the outer layer, there were considerable amounts in the middle layer. The concentration of tungsten in the innermost layer was only about twice that in the original steel. It is considered that the results with tungsten steel differed from those obtained with nickel and chromium, owing probably to the high vapour pressure of tungsten oxide. During the experiment some tungsten oxide was volatilised, and condensed in the cooler parts of the furnace. The uneven distribution of the tungsten in the three scale layers cannot be explained simply on the grounds of loss by volatilisation from the outer layers, for there was very much more tungsten in the innermost layer than in the original steel.

(6) *Vanadium Steel*.—The results for vanadium were somewhat similar to those for tungsten. The quantity of vanadium present was small, consequently the analytical results were rather unreliable, but qualitatively they show a concentration of vanadium in the inner scale layer, and small amounts only in the two outer layers.

(7) *Manganese Steel*.—The results obtained with the 3 per cent. manganese steel were exceptional. In the outer layer the manganese to iron ratio was about two-thirds of that in the original steel, while in the middle and innermost layers the ratio was a little greater than that in the original steel. It is remark-

able, however, that rather more manganese was present in the middle layer than in the innermost layer, this being the opposite to what was obtained in every other case. The results were confirmed by the manganese distribution in the scale layers produced on a mild steel containing 0.71 per cent. of manganese, the figures for which are also given in Table II. These results are particularly important in view of the presence of manganese in all steels, and the influence which manganese is considered by some steel makers to have on the melting point of the scale and the burning of ingots in the soaking pits.

(8) *Silicon Steel*.—Silica was completely absent in the two outer layers, the whole of the silica formed by the oxidation of the silicon in the steel being concentrated in the innermost layer, where, relative to the iron, it was present in an amount three times that in the original steel. No doubt the silica in the innermost layer was combined with some ferrous oxide as ferrous silicate, so that the layer consisted of a mechanical mixture of iron oxide and ferrous silicate. The layer was grey in colour.

Consideration of Results.

The irregular distribution of the alloying elements in the scale layers from alloy steels cannot be explained purely on the basis of differential oxidation, for the segregation and concentration occurred both in cases where the alloying element had a greater affinity (*e.g.* chromium) and a lesser affinity (*e.g.* nickel) for oxygen than the iron.

The segregation in the scale deposits would be impossible if the scale already formed were forced outwards by the formation of more scale. Considering the case of a chromium steel on this basis, if both chromium and iron were converted into oxide at the same time, the chromium oxide would remain disseminated through the scale, and if the mixed oxide were forced bodily outwards by further oxidation the chromium and iron would be present in a constant proportion throughout the specimens. Similarly in the case of a nickel steel, the nickel would remain disseminated through the scale in a finely divided metallic form, and would also be present throughout the specimen in a constant proportion relative to the iron.

The results can only be explained by supposing that the iron is removed from the zone of active oxidation and deposited free from other elements on the outside surface of the specimen.

Stead ⁽¹⁾ has drawn attention to the structure of nickel steel scale. He noted the presence of metallic particles in the inner scale layer on a 25 per cent. nickel steel, and assumed that the outer layer was free from metallic particles, not because nickel was absent, but because the outer layer, being the first to form, was oxidised under more intense conditions and hence oxidised as a whole. He states: "It is certain that when the oxidation is intense the metal is oxidised as a whole—a condition obtaining when the scale is thin. . . ."

His explanation of the mechanism of oxidation in the case of nickel steel is not satisfactory in view of the fact that nickel is absent from the outer layers of scale. It may be of interest to record that nickel oxide cannot exist in equilibrium with iron oxide containing more iron than 72 per cent. (that is, in equilibrium with the iron-rich solid solution described above, p. 513). Interesting results are obtained if a boat containing nickel oxide (NiO) be placed in a furnace together with a second boat containing crushed iron scale and the two heated *in vacuo* or in nitrogen. The scale absorbs oxygen from the nickel oxide until either the scale contains 28 per cent. of oxygen or until the whole of the nickel oxide is reduced to metal. The reaction is very rapid above 900° C. Nickel oxide is, of course, reduced to metal if it is heated in an oxygen-free atmosphere in the presence of iron, there being no need for the nickel oxide and the iron to be in contact. These reactions are due to the dissociation pressure of nickel oxide being greater than that of the iron-rich iron-oxygen solid solution. It will be seen, therefore, that nickel could only exist as oxide in that portion of the scale which contains less than 72 per cent. of iron—that is, in the surface layer which forms about 10 per cent. of the whole deposit. Actually, as has just been shown, nickel is not present in this layer in any form.

A simple explanation of what occurs when alloy steels are oxidised is available if the principle of diffusion in the scale be accepted. When an alloy steel is oxidised, a layer of scale is formed, the oxygen content of which varies from outside to inside, being greater at the outside. Solution of iron in the scale occurs

with the aid of oxygen, and diffusion of the iron outwards proceeds, while the oxygen gradient is maintained by the oxidation of the scale at the surface. The alloying elements are very nearly insoluble in the iron-oxygen solution, or if appreciably soluble can diffuse only at a very low rate. Consequently, while iron passes outwards rapidly, the alloying element either remains in the position which it occupied in the original steel or else moves outwards only very slowly. In certain cases this explanation requires expansion, notably in the cases of nickel and manganese.

When a nickel steel is first subjected to oxidation a thin layer of scale, consisting probably of both nickel oxide and iron oxide, is formed. During the oxidation the nickel-bearing portion is gradually buried beneath a continually thickening deposit of compact iron oxide, and as this layer becomes thicker it becomes richer in iron at its inner surface, where it is in contact with the nickel-bearing layer, and has as a consequence a lower dissociation pressure. As soon as the iron oxide in the vicinity of the nickel oxide contains more than 72 per cent. of iron the nickel oxide is reduced to the metal, and thereafter all nickel in the scale is in the metallic form. Oxidation of the iron proceeds along the crystal boundaries, which, in metals, are invariably less resistant to corrosion than the remainder. During the oxidation of nickel steels this effect becomes accentuated by the fact that oxidation of the crystals is delayed by the concentration of nickel at the scale-metal interface as a result of the withdrawal of iron. For oxidation to proceed, iron must diffuse outwards through the nickel-rich surface layer. Thus, while oxidation of the exposed surface of the crystals is delayed, the oxidation proceeds rapidly along the boundaries, owing partly to their natural susceptibility to oxidation and partly to the fact that at the extreme points of intercrystalline penetration a plentiful supply of iron is available without the occurrence of much diffusion. In this way the metallic crystals are separated from one another to a considerable depth by films of oxide. These crystals are then oxidised independently, the iron as it joins the scale being carried away by diffusion to the scale-air interface. Iron diffuses from the inner portion of each crystal of metal through the nickel-rich surface, while nickel diffuses inwards towards the centre of the crystal, with a tendency to keep the nickel concentration constant. Finally, each crystal

is converted into a grain of metallic nickel which occupies a position corresponding with that of the crystal from which it was derived. The nickel grains remain in the metallic form until the whole of the iron in the specimen has been oxidised. There can be little doubt that the exceptional heat resistance conferred upon iron by the presence of nickel is largely due to the necessity for interdiffusion of nickel and iron before oxidation can proceed.

Turning now to the case of manganese steel, the large amount of manganese present in the middle layer is explicable on the assumption that manganese oxide is readily soluble in the iron-rich iron-oxygen solid solution, but very much less soluble in the oxygen-rich solid solution of which the outer layer is largely or wholly composed. The distribution of manganese in the three layers would then be dependent on the partition coefficient. The presence of small amounts of nickel and chromium, and considerable amounts of tungsten and vanadium in the two outer layers of the corresponding scale, is readily accounted for on the same assumption—namely, a degree of solubility of the metals or their oxides in the iron-oxygen solid solution resulting in a distribution in the three layers in accordance with the corresponding partition coefficients. Silicon appears to be the only element which is totally insoluble in the scale, and hence entirely confined to the innermost layer, although nickel is very nearly in the same class.

In a number of cases a balance-sheet was prepared to show what became of the alloying element during the oxidation. An example is given for a 2.75 per cent. nickel steel.

Before Oxidation.

55.15 grm. of steel at 2.75% = 1.518 grm. nickel.

After Oxidation.

Layer 1	.	.	.	5.90 grm. at 0.00%	= 0.000 grm. nickel		
" 2	.	.	.	25.07 " " 0.16%	= 0.040 " "		
" 3	.	.	.	12.35 " " 7.07%	= 0.874 " "		
Unoxidised core	.	.	.	22.14 " " 2.75%	= 0.609 " "		
Total weight of nickel =					<u>1.523</u> grm.		

It is evident that there was no concentration of metallic nickel in the unoxidised core. Similar calculations for chromium and manganese led to similar results.

There remains one further point for consideration—that is, the inner altered zone mentioned in the case of nickel steel, but found to be present in nearly all the alloy steel cores. The general appearance of the zone has been illustrated in another paper⁽¹²⁾ (*loc. cit.*, Fig. 5). Under high magnifications the crystals in the altered zone are seen to have large numbers of small dark globules dispersed through them, the distribution of which does not appear to have been influenced at all by the crystal boundaries. This structure is common to iron and all ferrous alloys which have been oxidised *slowly*. It is readily produced by heating pure iron in contact with iron oxide *in vacuo*, and is, therefore, considered to be due to the absorption of oxygen by the metal, followed by the deposition of insoluble iron oxide. The structure is seldom seen in iron or in straight carbon steels, because complete oxidation generally proceeds at a faster rate than oxygen absorption by the metal. It is generally to be found in alloy steels, because such steels oxidise comparatively slowly.

The presence of the altered surface has a serious embrittling effect. $\frac{1}{2}$ -in. soft steel bars after a few hours' exposure at high temperatures to a *slightly* oxidising atmosphere are sometimes unable to withstand bending through 90° over a 1-in. radius without fracture, and bars which had become so brittle that they broke into pieces when dropped on a stone floor have been met with. The embrittlement is by no means so pronounced when the oxidising conditions are more severe.

CRYSTALLINE SCALE DEPOSITS.

Up to the present the discussion has centred round the scale deposits formed by oxidation in free air, the deposits under these conditions consisting of three layers. By progressively decreasing the oxygen pressure below that in the atmosphere (152 mm.), the outer scale layer becomes thinner and thinner in proportion to the total scale thickness, until at a certain critical pressure it is no longer present, and the scale deposit consists of two layers only. The disappearance of the outer layer is accompanied by a remarkable change in the appearance of the surface of the scale. The black velvet-like and almost structureless surface is replaced by a strikingly beautiful crystalline appearance; the surface is

no longer smooth, but is made up of crystal facets, causing a very marked relief. The crystals may be very minute or may be as much as $\frac{1}{4}$ in. across, while twin-like markings may often be seen. Fig. 5 (Plate LIX.) shows an example of the crystalline scale surface.

It is not suggested that the scale deposits produced in free air are not crystalline; on the contrary, it is quite certain that they are, but there is no possibility of confusing such scales with the very obviously crystalline deposits which are referred to here as "crystalline scales."

One of the most convenient ways of oxidising iron under reduced oxygen pressure is to carry out the oxidation in a stream of air moving at a carefully controlled rate. The oxidation of the iron depletes the atmosphere of oxygen, so lowering the partial pressure, and if the conditions are suitable, crystalline scale will result. A large number of experiments have been carried out to determine the types of structure which may be produced by varying the rate of air supply and the temperature.

The available supply being limited, only a few experiments were made with cold-rolled electrolytic iron; the remainder were carried out with a decarburised steel containing Mn 0.7, Si 0.006, S 0.028, and P 0.016 per cent. It was found that the structure of the scale was (within wide limits) independent of the composition of the iron. The cold-rolled sheet— $\frac{1}{8}$ in. thick—was cut into pieces about $\frac{3}{4}$ in. square, the surfaces being filed smooth and flat and finished on emery-cloth. A piece, the exact dimensions of which were known, was then placed in a slotted fireclay boat so that one surface made such an angle with the incoming air stream that the oxidation of the surface was uniform; there was then very little oxidation of the back surface. The angle was found by trial and error, and varied with the rate of air supply and with the temperature. With an incorrect setting the oxidation was uneven, the results could not easily be repeated, and definite conclusions could not be drawn.

The furnace employed was an electrically heated silica tube of $1\frac{1}{4}$ -in. bore. The boat and specimen were pushed into the hot furnace while a stream of nitrogen passed in the reverse direction. The end of the furnace was then closed by a bung and "Arnold" bulb sulphuric acid seal, the nitrogen stream was cut off, and air

dried by sulphuric acid was passed into the furnace at a constant rate with the aid of two aspirators. At the conclusion of the experiment the boat was withdrawn and the specimen allowed to cool rapidly in air. The time of oxidation was varied from 4 days to 1 hr., according to the rate of air supply.

It was found that the structure of the scale varied very much with the rate of oxidation, with the time of oxidation, and also with the temperature. It is difficult to describe these structures, but they fall naturally into four types, which are illustrated.

In addition to the structural features characteristic of the four main types, other details may appear, such as the growth of pyramids and needles as projections from the crystal faces, and also the formation of depressions on the crystal faces, which may be described as negative crystals or etch pits. It must be pointed out that none of these scales was etched or treated in any way to develop the structure; the micrographs show the scale exactly as it developed during the oxidation.

Type 1. Low Relief; Irregular Orientation.—The structure is illustrated in Fig. 7 (Plate LIX.); it shows crystal grains, each having a number of crystal faces exposed. In many crystals an appearance resembling twin bands may be seen, but it is due to striations on the crystal faces. All orientations appear to be represented.

Type 1A. Low Relief; Regular Orientation.—This structure is illustrated in Fig. 8. There is a general appearance of striations in two directions at right angles. Actually the individual scale crystals are small, and have very nearly the same appearance as those of which type 1 is composed, but in type 1A these crystals all appear to have very nearly the same orientation. The reason for this will be discussed later.

Type 2. High Relief.—The structure is shown in Fig. 9 (Plate LX.). The relief is very much greater than in types 1 and 1A, due to the crystal faces having a different form.

Type 3. Idiomorphic Crystals.—The structure consists of almost perfectly developed crystals growing upwards from a lower layer of scale. These crystals may be broken away with ease, and on some crystals as many as eight faces may be seen under the binocular microscope. The structure may be produced either with the idiomorphic crystals oriented at random as in Fig. 10,

or with a regular orientation as in Fig. 11. The reason for the regularity of orientation in the latter case will also be discussed later.

Type 4. Transition Stage to Smooth.—The idiomorphic type 4 structure passes by stages (not illustrated) into the smooth scale surface characteristic of rapid oxidation.

The scale structures so far described and illustrated are by no means the only ones which may be produced. Rates intermediate between those producing types 1 and 1A result in the growth of multitudes of fine needle-like prismatic crystals when the rate is nearer that producing the type 1, and large numbers of pyramids on square bases (the form is almost certainly [111] of the cubic system) when the rate is nearer that for type 1A. No satisfactory photograph of the needles could be obtained, but the growth of pyramids on a background of the type 1A structure is shown in Fig. 12. The black squares are the pyramids.

Figs. 13 and 14 (Plate LXI.) show the transition stage between types 1A and 2. In the corresponding specimens the rate of oxidation was faster at the top, so that type 2 was produced, and slower at the bottom, giving type 1A. Reference will be made later to the orientation of the scale crystals in the lower portions of these two illustrations.

In Table III. details are given of the rate of oxidation producing the structures which have been described and illustrated; figures are also given for the reduction in thickness of the specimens. The figures for the volume of air per sq. cm. per hr. and the weight of oxygen per sq. cm. per hr. are calculated from the volume of air passed and the area of one face only of the specimen. The reduction in thickness was measured after removing the scale deposit and removing irregularities from the surface by judicious filing. These figures give a measure of the actual amount of oxidation, as distinct from the amount of oxygen supplied.

From Table III. the rates of oxidation for each type of structure may readily be seen. The critical rate of oxidation, below which crystalline scales are produced and above which smooth scales result, is 23.9 c.c. per sq. cm. per hr. The results given in this table only apply for the temperature stated, namely, 930° C. At higher temperatures the critical rate is higher, and the dividing rates between the different types are higher also.

TABLE III.—*Oxidation of Decarburised Steel Sheet at 930° C. in a Controlled Air Stream.*

No. of Specimen.	Period of Oxidation. Hr.	Volume of Air. C.c. per sq. cm. per hr.	Weight of O ₂ . Mg. per sq. cm. per hr.	Reduction in Thickness. Mm.	Reduction. Mm. per hr.	Type of Structure.
1	46.0	2.2	0.6	0.087	0.0019	1 } Low relief, irregu-
3	93.0	3.0	0.8	0.260	0.0028	1 } lar orientation
6	23.5	5.1	1.4	0.089	0.0038	1A, with needles
9	47.0	6.6	1.9	0.252	0.0054	1A, with pyramids
14	23.0	8.3	2.3	0.184	0.008	1A } Low relief, regu-
16	22.7	12.2	3.5	0.273	0.012	1A } lar orientation
21	24.0	15.3	4.3	0.360	0.015	1A, passing to 2
25	23.0	15.3	4.3	0.345	0.015	1A, passing to 2
21A	46.0	18.2	5.2	0.782	0.017	2, High relief
26	23.7	21.8	6.2	0.427	0.018	2, passing to 3
33	18.3	25.3	7.2	0.348	0.019	2, passing to 3
32	23.0	22.2	6.3	0.391	0.017	3 } Idiomorphic
42	23.7	23.9	6.8	0.427	0.018	3 }
41	24.0	23.8	6.8	0.427	0.018	4 } Transition from
30	24.0	25.8	7.3	0.456	0.019	4 } idiomorphic to
39	25.8	28.6	8.1	0.542	0.021	4 } smooth
49	23.3	31.0	8.8	0.513	0.022	4 }
55	21.0	62.2	17.6	1.218	0.058	} Smooth ; 3-layer type
59	2.1	143.0	40.0	0.289	0.139	
61	1.8	425.0	120.0	0.433	0.236	

and at lower temperatures the rates are lower. As examples, the critical rates for three other temperatures are given in Table IV. :

TABLE IV.—*Effect of Temperature on Critical Rate of Oxidation.*

No. of Test.	Temperature. ° C.	Period. Hr.	Volume of Air. C.c. per sq. cm. per hr.	Weight of Oxygen. Mg. per sq. cm. per hr.	Reduction in Thickness. Mm. per hr.
106B	800	23.0	16.1	4.56	0.011
K	875	23.0	18.7	5.30	0.014
42	930	23.7	23.9	6.80	0.018
97H	1000	23.0	60.5	17.15	0.053

Effect of Time of Oxidation.—Increasing the time of oxidation has an effect similar to, but not so marked as, an increase in the rate of oxidation. As oxidation proceeds at a certain rate the scale crystals pass from the low-relief to the high-relief types, and finally the crystalline structure is replaced by a smooth and

structureless surface. As will be seen from Table III., each type is produced over a considerable range of oxygen supply, and if the rate of oxidation be kept constant at a value corresponding to the centre of the range for one type it is necessary to continue the oxidation for several days before the resulting structure falls within the next higher type. Thus, while the results given in Table III. are only strictly true for times of the order of 24 hr., they are approximately correct for both much longer and much shorter times.

The Relation between the Crystalline Character of the Scale and that of the Iron from which it is formed.—The crystalline scale first produced on a polished iron specimen takes its crystalline form from the iron crystals from which it is produced. The scale crystals correspond exactly in size, shape, and position with the ferrite crystals of the iron, and it is not unreasonable to suppose that they have also an orientation corresponding with that of the ferrite grains from which they formed. The first-formed scale crystals are, therefore, pseudomorphous* after the ferrite crystals. This relation is only true when the ferrite crystals are fairly small. When a very large ferrite crystal is oxidised, more than one scale crystal is formed on the surface, and this may be due to several simple causes, which need not be considered here in detail.

Fig. 15 (Plate LXI.) shows the polished and etched surface of finely crystalline iron, the area having been marked for identification by means of scratches; Fig. 16 shows the same area after oxidation. The specimen was heated to 1000° C. in 1 hr., held at that temperature for 30 min., and cooled to about 200° C. in 2 hr.; the furnace atmosphere was CO₂ under reduced pressure. There can be no question that the scale crystals correspond with the ferrite crystals shown in the previous micrograph. The result confirms the observations of Carpenter and Elam,⁽¹¹⁾ to which further reference will be made later.

Similarity of Orientation in Scale Crystals.—It is now possible to explain the remarkable uniformity of orientation exhibited by the scale crystals in some cases. The iron used for these

* The word is not intended to convey the idea that the oxide crystals exist in a form foreign to their nature, but that they are produced from the ferrite crystals without change in orientation. Neither "isomorphous" nor "parallel growth" meet the case exactly.

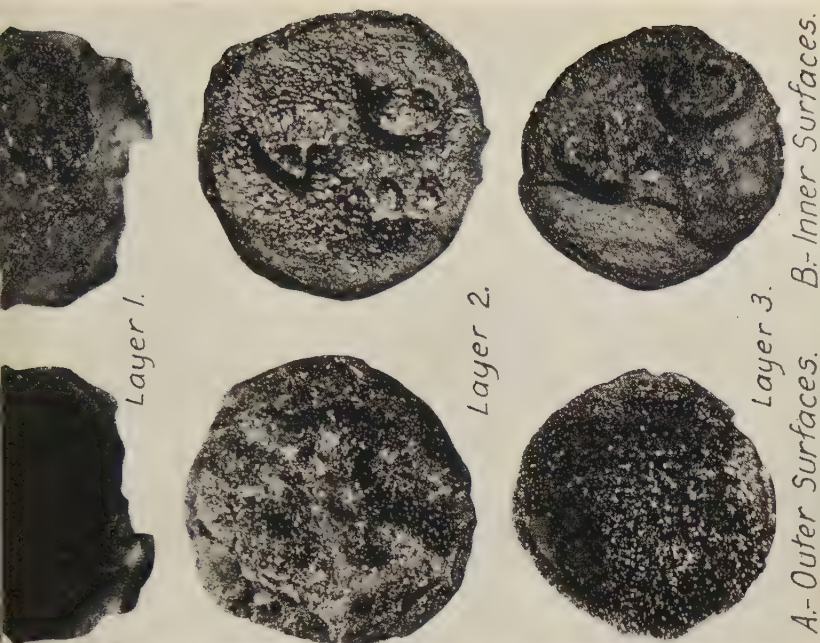


FIG. 2.—Obverse and reverse of three scale layers.
(Oblique illumination.) $\times 2$.



FIG. 1.—Layer formation in various steels. (Natural size.)
1=outside layer ; 2=middle layer ;
3=inside layer ; 4=metallic core.

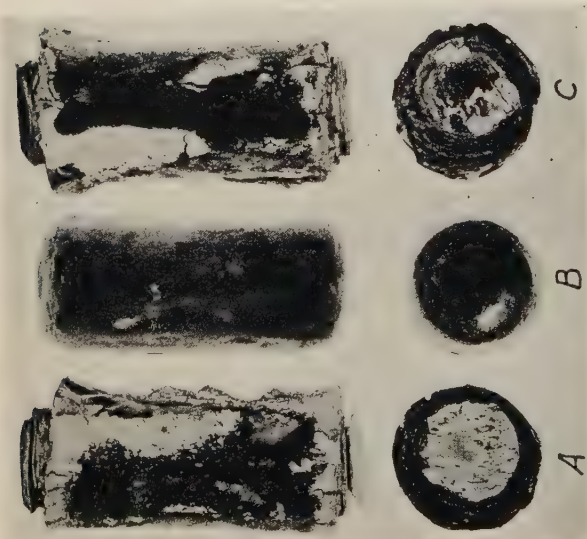


FIG. 3.—Disintegrated scale on severely oxidized iron. *A* and *C* received lead oxide treatment; *B* untreated. (Natural size.)

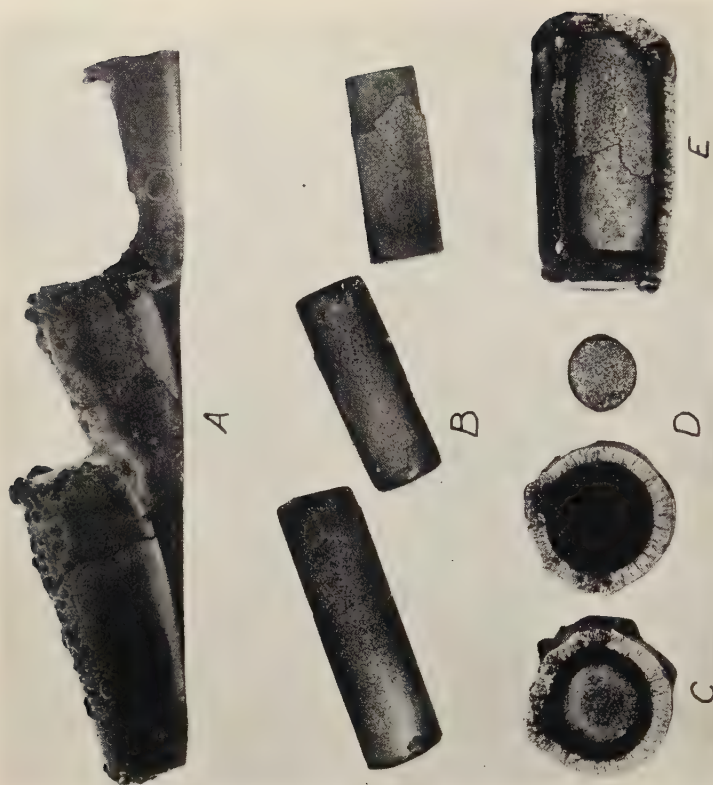


FIG. 4.—Loose core type. (Approx. natural size.) *A*, External appearance. *B*, Unoxidized cores removed from scale shells. *C* and *D*, Scale and core in section. *E*, Scale broken away to expose loose core.

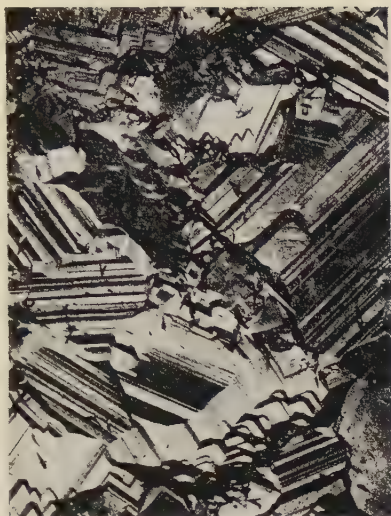


FIG. 5.—Crystalline scale. (Oblique illumination.) $\times 10$.

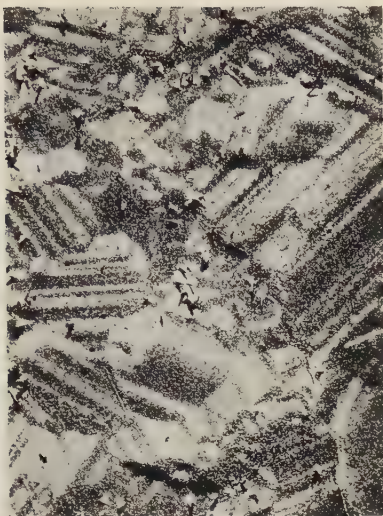


FIG. 6.—Same area as Fig. 5 after heating for 30 min. in air. (Oblique illumination.) $\times 10$.

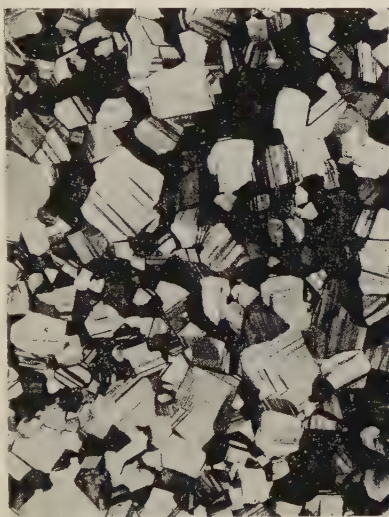


FIG. 7.—Type 1. Low relief, irregular orientation. (Oblique illumination.) $\times 10$.



FIG. 8.—Type 1A. Low relief, regular orientation. (Oblique illumination.) $\times 10$.

(The above micrographs were reduced to two-thirds linear in reproduction.)



FIG. 9.—Type 2. High relief. (Oblique illumination.) $\times 10$.



FIG. 10.—Type 3. Idiomorphic, random orientation. (Oblique illumination.) $\times 10$.



FIG. 11.—Type 3. Idiomorphic, regular orientation. (Oblique illumination.) $\times 10$.



FIG. 12.—Pyramids growing on the surface of Type 1A. (Slightly oblique illumination.) $\times 10$.

(The above micrographs were reduced to two-thirds linear in reproduction.)

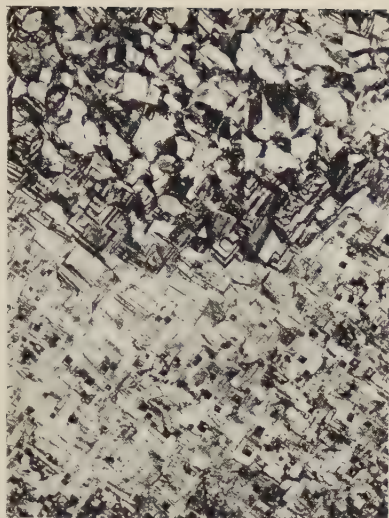


FIG. 13.—Transition from Types 1A to 2. Direction of rolling vertical, surface polished. (Oblique illumination.) $\times 10$.



FIG. 14.—Transition from Types 1A to 2. Direction of rolling vertical, surface filed at 45° . (Oblique illumination.) $\times 10$.

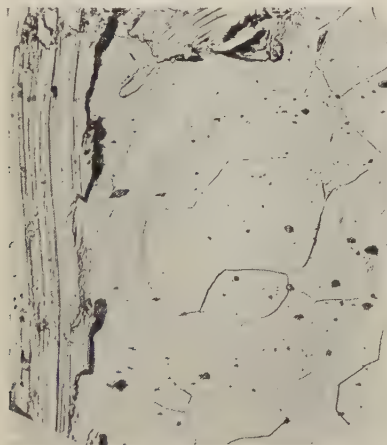


FIG. 15.—Ferrite grains. (Vertical illumination.) $\times 350$.



FIG. 16.—Scale crystals, same area as Fig. 15. (Oblique illumination.) $\times 350$.

(The above micrographs were reduced to two-thirds linear in reproduction.)



FIG. 17.—Crystal growth in scale, 2 periods = 4 hours. (Oblique illumination.) $\times 10$.



FIG. 18.—Same area as Fig. 17, 5 periods = 10 hours. (Oblique illumination.) $\times 10$.



FIG. 19.—Same area as Figs. 17 and 18, 11 periods = 22 hours. (Oblique illumination.) $\times 10$.



FIG. 20.—Crystalline scale produced by heating for 24 hours at 1000°C . in CO_2 . (Oblique illumination.) $\times 10$.

(The above micrographs were reduced to two-thirds linear in reproduction.)

experiments was very severely cold-rolled, the rolling having been carried out always in the same direction. This treatment is known to lead to the development of a similarity of orientation in the crystals, which, there is good reason to suppose, persisted after the recrystallisation occurring in this material at about 500° C. Since the orientation of the scale crystals is determined by that of the iron, scale which begins to form before the critical temperature is passed will exhibit a similarity of orientation in the grains, while that which begins to form only after the α - γ change has occurred will show no marked orientational similarity.

In the determinations of the effect of rate of flow on the crystal structure, the hot furnace was filled with nitrogen before the specimen was introduced. It is very possible, therefore, that when the rate of air supply was exceedingly slow (less than 5 c.c. per hr.) the specimen had passed through the Ac_3 point before oxidation commenced, and thus the scale crystals showed little or no similarity of orientation. When the air supply was more rapid, oxidation began before the similarity of orientation in the iron was destroyed, and as a consequence a similarity of orientation was manifest in the scale crystals.

A second factor which shares in the determination of the orientation of the scale crystals is the nature of the preparation of the initial metallic surface. When the surface before oxidation had been polished carefully as for a metallographic specimen, and also when it was finished by filing or grinding in a direction parallel with, or at right angles to, the direction of rolling (see Fig. 8, Plate LIX.), any similarity of orientation developed in the scale crystals was made evident by striations at 45° to the direction of rolling. If, however, the specimen were finished by filing and grinding in a direction at 45° to the direction of rolling, the similarity of orientation in the scale crystals was made manifest by striations parallel with and at right angles to the direction of rolling. The differences between Figs. 13 and 14 (Plate LXI.) are entirely due to differences in surface finish; both specimens were oxidised at the same rate for the same time, and were placed in the furnace in the same position relative to the direction of rolling, but whereas Fig. 13 represents a specimen finished by careful polishing, Fig. 14 represents a specimen finished by filing at 45° to the direction of rolling. The variation in the scale structure

in each micrograph is due to a lack of uniformity in the rate of oxidation, to which reference has already been made (see p. 534).

It is possible that a third factor plays a part in producing a similarity of orientation in the scale crystals—namely, crystal growth in the scale ; this will be discussed next.

Crystal Growth in Scale.—The size of the scale crystals increased with the time of oxidation. When the iron was finely crystalline, the scale first formed was composed of very minute crystals, but after continuing the oxidation for a long time the crystals became very large—crystals of scale up to $\frac{1}{4}$ in. in diam. were produced by continuing the oxidation for several days.

Experiment showed very definitely that it was only the first film of scale which formed as a pseudomorph of the ferrite. Further oxidation resulted in the growth of some of the scale crystals at a faster rate than the others, so that eventually only a few survived on the surface, the remainder being buried by the larger ones.

Micrographs of the same area illustrating this crystal growth are reproduced in Figs. 17 to 19 (Plate LXII.). The specimen was heated under suitable conditions of slow oxidation for a series of two-hour periods at 1000° C., slow heating and slow cooling being necessary each time to avoid cracking and loosening the scale deposit. The slow cooling which was necessary had the disadvantage of producing a dulled surface on the crystals which detracted from their beauty. After each two-hour period a micrograph was taken (only three are reproduced). Fig. 17, taken after four hours, shows a finely crystalline structure with a few considerably larger crystals ; the latter developed during the second period of heating. Fig. 18, taken after five periods, shows that further growth had occurred in the larger crystals which were visible in Fig. 17, while many other crystals had also grown ; in particular, a large crystal may be seen at the top right-hand corner. Fig. 19 was taken after eleven periods ; the crystals are now very large, and the structure bears no resemblance to that in the first illustration. Some difficulty may be found in tracing the relationship between Figs. 18 and 19.

Conditions under which Crystalline Scale may be Produced.—The only condition which must be satisfied in order to produce crystalline scale is that the rate of oxidation must be below a

certain critical value. There are many methods of satisfying this condition, some of which are set out below :

(a) Iron may be heated in an atmosphere of pure oxygen at very low pressure.

(b) Iron may be heated in a stream of CO_2 at atmospheric pressure. Fig. 20 shows the characteristic appearance of scale produced in this way. The stepped surface of the crystals is not common to all specimens oxidised in CO_2 , nor is it obtained only by oxidation in that medium, but it is more easily produced in this way than by any other means. The scale contains about 75.5 per cent. of iron, the percentage varying with the conditions.

(c) Crystalline scale results when iron is heated in a slow stream of steam. The scale contains about 75 per cent. of iron, the value varying somewhat with the conditions.

(d) If iron and iron oxide are heated in proximity either *in vacuo* or in an oxygen-free atmosphere, crystalline scale forms on the iron. The character of the scale deposit varies with the time and temperature as in all other cases, but it also varies with the quantity and composition of the iron oxide. The type is practically independent of the distance separating the iron from the oxide. At the high temperature the iron oxide dissociates, owing to the partial pressure of the oxygen in the furnace atmosphere being less than the dissociation pressure of the oxide. The oxygen in the atmosphere oxidises the iron ; the scale formed on the iron contains less oxygen than the oxide which is the source of the oxygen ; the iron oxide continually becomes poorer in oxygen, and oxidation ceases when the oxide and the crystalline scale have the same composition.

(e) Iron heated with nickel oxide *in vacuo* or in an oxygen-free atmosphere results in crystalline scale deposits. The nickel oxide dissociates thus : $2\text{NiO} = 2\text{Ni} + \text{O}_2$. If sufficient time be allowed, the nickel oxide is completely reduced to metal, the oxygen forming with the iron a crystalline scale deposit. The reduction of NiO by iron has been demonstrated by Stead.⁽¹⁾

(f) Iron heated with copper oxide *in vacuo* or in an oxygen-free atmosphere results in the formation of crystalline scale. The changes taking place are similar to those occurring in the case of nickel oxide. The results are complicated by the volatility of copper oxide, a deposit of metallic copper on the iron resulting

from the decomposition of the copper oxide vapour. The reduction of copper oxide by metallic iron has also been demonstrated by Stead.⁽¹⁾

(g) When iron is heated with copper *in vacuo* crystalline scale forms on the iron. This statement is only true when the copper contains oxygen in some form (as Cu_2O , or as CO_2 and H_2O , in solution in the copper or filling the blowholes). Copper which has been heated in hydrogen will not cause the oxidation of iron. It is difficult to say with certainty whether the oxygen present in the copper as copper oxide or that present as CO_2 and H_2O is the more important. Experiment shows that copper showing only very minute quantities of oxide under the microscope may have a powerful oxidising effect, and this makes it probable that it is CO_2 and steam evolved on heating *in vacuo* which supply the bulk of the oxygen.

Carpenter and Elam⁽¹¹⁾ have described the formation of crystalline scale deposits on iron. The specimens were prepared by heating iron and copper together *in vacuo*, and they attributed the scale formation to the oxidising gases evolved by the copper and the iron on heating. They found that "The oxide of iron originally produced is isomorphous with α -iron, and the orientation of the oxide produced on any given crystal of iron is determined by the orientation of the α -iron itself." Their work is fully confirmed by the present research, but it is now evident that the crystalline scale may be produced under widely varying conditions. The iron may have any composition; pure electrolytic iron, high and low carbon steels, alloy steels, and cast iron all behave in the same way, provided the partial pressure of the oxygen is suited to the other experimental conditions. It is almost immaterial whether the oxygen be supplied as gaseous oxygen at a low pressure, as an oxygen and inert gas mixture, as a reactive gas like CO_2 , or as a compound, such as iron oxide, which gives off oxygen owing to dissociation. Above all, there is no indication that the presence of any elements other than iron and oxygen is necessary for the development of the remarkable structures in question.

The Cause of Variations in the Type of Crystalline Scale.—Variations in the appearance of the scale are mainly dependent on the form of the crystal faces. There is good reason to suppose

that a solid solution series belonging to the cubic system exists at high temperatures over the composition range of crystalline scales. Many different forms belong to the cubic system, the commonest developed in magnetite being the cube, the octahedron, and the rhombododecahedron. It is often found that the forms which develop in a substance vary with the conditions (temperature, pressure, &c.) under which the crystals grow. The crystalline scales included in Table III. were produced under conditions permitting two important variables: (a) the rate of crystal growth (rate of oxidation), and (b) the actual composition of the crystals. In Table V. a few results are given to indicate the

TABLE V.—*Effect of Rate of Oxidation on Composition of Crystalline Scale Layers.*

Temperature of oxidation, 930° C.

No. of Specimen.	Rate of Air Supply. C.c. per sq. cm. per hr.	Period. Hr.	Iron. %	Type of Structure.
3	3	93	76.5	1, Low relief, irregular orientation
8	6	47	76.2	1A, Low relief, regular orientation
38	20	21	76.2	2, High relief
44	23	23	75.0	3, Idiomorphic
51	32	22	74.3	4, Idiomorphic passing to smooth
55	62	21	{ 71.2 } { 74.7 }	5, Smooth { outside layer middle layer

relations between composition, rate of oxidation, and type of crystalline structure. It will be seen that there is a decrease in the iron content of the crystalline scale on passing from the lower to the higher rates of oxidation.

Although the variations in composition are small, it must be remembered that a change in iron content of less than 8 per cent. covers the whole range from Fe_2O_3 to FeO . It is reasonable, therefore, to ascribe the cause of the variation in the principal form of the crystals to variations in their composition rather than to variations in the rate of growth.

Destruction of Crystalline Scale.—It has already been stated that the formation of crystalline scales appears to coincide with the disappearance of the outside highly oxidised layer normally

present in scale deposits. If a specimen exhibiting crystalline scale be reheated under conditions of more rapid oxidation, the crystalline structure is gradually destroyed by the formation of a structureless surface deposit, which has the same characteristics as the outer layer of the three that form under normal conditions of rapid oxidation.

Fig. 5 (Plate LIX.) shows an example of coarsely crystalline scale, to which reference has already been made. Fig. 6 shows the same area after the specimen had been reheated in a plentiful supply of air for 30 min.; it is readily recognisable as the same area as Fig. 5, but the finer details are now lost. More prolonged oxidation resulted finally in the complete disappearance of the large faceted crystals.

It is of importance to decide whether the disappearance of the crystalline scale takes place as a result of the disintegration of the crystals, or as a result of the deposition of structureless material on the crystalline surface. In this connection the differences which develop on heating in a plentiful supply of air two similar samples of scale, one attached to the iron core so that oxidation of the iron proceeds, and the other free from the iron backing, are noteworthy. In both cases the crystalline structure is marred by the oxidising effect of the air, but whereas the detached scale is marred only to a limited extent, insufficient to destroy entirely the coarsely crystalline appearance however long the oxidation is continued, the scale attached to the iron is rapidly converted into the smooth structureless form. It is clear, therefore, that the disappearance of the crystalline structure is not a simple recrystallisation effect, such as might be anticipated from the fact that ferric oxide (the final product when any iron oxide is heated in air) is hexagonal, while magnetic and ferrous oxides are cubic. The detached scale is converted completely into ferric oxide by heating in air, and thus the crystals may be looked upon as pseudomorphs, the transition involving only a limited destruction of the crystal facets. The scale attached to the iron is not converted into ferric oxide, the iron content being lowered only a little, owing mainly to a development of the new structureless outer layer containing about 71.5 per cent. of iron. In Fig. 6 (Plate LIX.) small projecting needles may be seen, and a careful examination will reveal the same needles in Fig. 5.

These needles are not destroyed by the increased rate of oxidation, but as rapid oxidation proceeds they become more and more buried, until finally they disappear. It is clear that structureless oxide of iron is deposited on the surface, and is not produced solely by the disintegration of the surface layer.

Explanation of the Formation of Crystalline Scale on the Basis of the Diffusion Hypothesis.

How iron oxide crystals exhibiting plane faces can develop under the conditions of experiment requires an explanation. Idiomorphic iron oxide crystals are common in nature, but such crystals have been formed either by crystallisation from a rock magma or from aqueous solution. Idiomorphic crystals may also result by condensation from a vapour phase.

It is abundantly clear that the large scale crystals in question are not pseudomorphs of the iron crystals, for such a suggestion is entirely at variance with the facts which have been recorded. In these experiments there was no liquid phase from which the crystals could have been deposited, and, in addition, the crystalline structure was visible before the specimens cooled. It is exceedingly improbable that an iron-bearing vapour existed in all the experiments in a quantity sufficient to allow a plausible explanation of the phenomenon to be devised. Crystalline scale has been produced by heating together *in vacuo* electrolytic iron and ferric oxide derived from electrolytic iron. No doubt, minute traces of carbon, silicon, manganese, sulphur, and phosphorus were present, and probably also minute quantities of residual gases, since the vacuum was only about 0.01 mm. But it is difficult to see how even minute traces of iron-bearing vapour could be formed from these components at so low a temperature as 800° C. Even allowing the possibility of minute quantities of iron-bearing vapour, the difficulty of showing how the iron can distil from and condense upon one and the same point still remains. If the possibility of the diffusion of iron or iron oxide from the metallic core through the scale to the surface be admitted, a simple explanation of the development of crystalline scale is at once available.

The scale deposit consists of a solid solution of iron and oxygen, the solution extending over the range from 72.0 per cent.

of iron upwards to FeO . Iron is dissolved in this solution and diffuses outwards.

Low-Oxygen Pressure.—If the oxygen pressure be sufficiently low, the solid solution will extend from the core to the scale surface, and the iron will diffuse outwards to the surface, where it will find a place in the crystalline structure in accordance with the forces there developed.

It is possible that the scale crystals are anisotropic to diffusion, and a variation in the rate of diffusion with the orientation of the crystal may play a part in the development of the crystal facets, and may also cause some crystals to grow at a greater rate than others. It may be taken for granted that there are forces in existence at the surface of the crystals which will tend to cause atoms of iron or molecules of iron oxide arriving at that surface to take up such positions as will result in the development of plane faces.

When oxidation first sets in, extremely thin pseudomorphs of the ferrite crystals are produced, but once this oxide film has been produced the metallic base plays no further part in the orientation, size, or shape of the oxide crystals, and acts simply as a source of iron. Even when oxidation occurs above 900°C ., it is the ferrite crystals, and not the austenite crystals, which determine the initial orientation of the scale crystals, for the oxidation begins before the transition. It is possible that a different appearance would be obtained in the scale if oxidation were prevented until γ -iron had formed, for then, no doubt, the first film of scale would take its orientation from the γ crystals.

As oxidation proceeds, some of the scale crystals grow more rapidly than others. This is due to their having a more favourable setting with respect to the direction of most rapid diffusion. The more rapidly growing crystals envelop or "pinch out" the slow-growing ones, so that after a short time there is no longer any resemblance between the scale structure and that of the original iron. The disappearance of the less favourably oriented scale crystals proceeds so long as oxidation is continued, so that eventually the survivors may be as much as $\frac{1}{4}$ in. in diam.

It is probable that the more rapidly growing crystals, besides enveloping the slow-growing ones, gradually absorb them, for the large crystals produced by prolonged oxidation and visible on

the surface pass almost through the scale layer; they do not reach the metal core, for they are always separated from it by the loose innermost layer, to which reference has already been made.

High-Oxygen Pressure.—When the oxygen pressure at the surface is high there is no longer a continuous series of solid solutions of iron and oxygen from the core to the scale surface. The oxygen content of the surface scale is greater than the solubility in the cubic phase, and a second hexagonal phase appears. This second phase is also a solid solution, ranging in composition from Fe_2O_3 to near Fe_3O_4 . After diffusing outwards through the cubic and inner portion of the scale, the iron passes to the outer layer, which consists either of the hexagonal phase or of a mixture of the hexagonal and cubic phases. Owing either to the presence of two phases or to the specific properties of the hexagonal phase, the *coarsely* crystalline surface appearance does not develop in this highly oxidised layer.

SUMMARY AND CONCLUSIONS.

An explanation of the mechanism of the oxidation of iron and steel must deal satisfactorily with the four following points:

1. The scale is normally smooth, compact, and free from cracks and fissures in spite of the oxidation involving an expansion of the order of 100 per cent.

2. The scale consists normally of three very distinct layers, differing in appearance, structure, and composition. With a few exceptions, non-ferrous elements present in iron before the oxidation are concentrated in the innermost of the three layers of scale.

3. Foreign substances placed on the surface of the iron are not forced away by the formation of the scale, but remain unmoved and become completely enveloped by the scale.

4. When oxidation is slow the formation of large scale crystals exhibiting plain crystal faces occurs, the scale surface sometimes showing high relief.

These experimental facts are incompatible with the commonly accepted view that the outside of the scale is that which formed

at the initiation of oxidation, further oxidation having displaced the first-formed scale bodily outwards. This hypothesis must therefore be discarded.

The facts indicate clearly that the outer part of the scale is the last to form, the middle portion being the first. Such a mechanism would be possible if a volatile compound of iron of transitory existence played a part. No such iron-bearing vapour is known, and the experimental conditions have in some cases been such as to prohibit the formation in appreciable quantity of any compounds other than those of iron and oxygen.

The only remaining mechanism of oxidation consistent with the facts is that of counter-current diffusion—the iron diffusing outwards and the oxygen inwards through the scale deposit—and it is hoped that the evidence which has been brought forward here will be regarded as proving the diffusion hypothesis. It is not of essential importance whether the iron diffuses as iron atoms or in some other form. It is difficult to picture the diffusion of iron combined with oxygen (as ferrous oxide, for example) in a solid solution of iron and oxygen, and consequently for the sake of simplicity the diffusion of iron atoms has been described. Reference has been made to the solution of iron in the scale. It is immaterial whether the iron be converted into ferrous oxide first and then dissolved in the scale, or whether the iron dissolves directly in the scale. The essential feature is that scale is normally unsaturated with iron, and that metallic iron will join such scale if the two are heated in contact.

It is perhaps unwise to make speculative deductions until further experimental work has been carried out, but it does seem probable that useful results might be obtained by the study of heat-resisting steels along the lines indicated above. An attempt is being made to investigate the microstructures of scale deposits with a view to throwing further light on the problem of heat resistance. Considerable difficulties have been encountered in the preparation of suitable specimens, but interesting results have already been obtained.

The author wishes to record his thanks to Professor C. A. Edwards, D.Sc., for supplying facilities for the carrying out of the experimental work recorded in this paper.

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DISCUSSION.

Professor H. C. H. CARPENTER, F.R.S. (Hon.-Treasurer), expressed his special interest in the way in which the author linked up the structures which Miss Elam and he (Professor Carpenter) had obtained and published before the Institute some seven years ago, and showed how they conformed to the graduated oxidation process which he described. As to the idea of the iron diffusing outwards, he thought the author was wise in leaving the question open whether it went as the metal or as an oxide, but something of that kind appeared to take place, and there was a counter-current movement of oxygen. That seemed a plausible and reasonable view to take of the process which fitted in with the facts. The greater resistance of alloy steels to oxidation also fitted in admirably with the view of the oxidation process put forward in the paper. He hoped the author would be able to do some X-ray work, which would no doubt throw some interesting light on the changes which took place.

Mr. ULICK R. EVANS (Cambridge) said the author had put forward a new mechanism of oxidation, and had adduced very convincing evidence in its favour. If one compared that mechanism with the mechanism put forward by Pilling and Bedworth some years ago in their work on the oxidation of copper,¹ at first sight they seemed to be two ways of describing the same process; Pilling said the oxygen moved relatively to the metal, while the author said the metal moved relatively to the oxygen. If one looked closely into the matter, however, one found the two ideas were fundamentally different; it was not simply a question of choice of a frame of reference. That was best seen if one considered the case of a metal which was supposed to have only one oxide, whose theoretical composition, as given in the textbooks, was M_xO_y , where M was the metal. According to the Pilling mechanism of diffusion, the oxide layer had the theoretical composition M_xO_y at the inner face, and an excess of oxygen at the outer face; with the Pfeil type of diffusion, it would have the theoretical composition at the outer face, and excess of metal at the inner face. In both cases there was a composition gradient, and diffusion would occur in such a direction as to reduce the differences in composition. There could also be an intermediate case where the oxygen content was super-normal on the outside and sub-normal on the inside.

It seemed to him that from the practical point of view there was a very important difference between the various cases. If one assumed that the oxide on the outside could not take up any excess oxygen beyond its "theoretical content," then whatever the oxygen pressure

¹ *Journal of the Institute of Metals*, 1923, No. 1, p. 529.

in the gases one could not get any increase in the composition gradient, and consequently the metal should oxidise at the same rate at all pressures. If, on the other hand, excess of oxygen could be taken up as the pressure increased, the gradient would increase with the pressure; the velocity constant would therefore increase with the pressure, until sooner or later one began to get a second oxide phase, an occurrence which would "fix" at a definite value the excess oxygen concentration at the outer surface of the first phase. At that pressure the gradient would cease to rise, and the effective velocity constant would no longer increase with the pressure. But, finally, as the effect of the second phase became more and more important, the influence of the oxygen pressure upon that second layer would be felt, and there would be a slow rise in the effective velocity again. If, therefore, the oxidation velocity constant were to be plotted against the pressure, the curve would rise steeply at low pressures, then become almost horizontal, and then gradually begin to rise again.

That was just the sort of curve which Pilling and Bedworth found in the case of copper, and that agreement would seem to show that in the case of copper the mechanism of oxidation was not very different from that which those authors described, although probably some slight modification of their ideas was necessary. Dr. Pfeil, however, had made out a very good case for his own mechanism in the case of iron. The conclusion seemed to emerge that different mechanisms might operate in different materials, and therefore probably the materials which behaved best at comparatively low-oxygen pressures might not be the ones which would behave best at high-oxygen pressures. That, he thought, had some practical importance in view of the tendency in engineering and industry to utilise higher pressures, combined with high temperatures.

He wished to say it was not oxygen concentration alone which was important in determining the rate of oxidation; as Hatfield had shown very clearly,¹ the presence of various impurities, and particularly sulphur dioxide, had great influence, possibly because in the presence of such substances the oxide was in part formed by complicated secondary reactions (for instance, by the decomposition of sulphates which had been formed temporarily), and so an oxide of quite a different character was obtained which would probably be very much more permeable.

He would also like to draw attention to some recent work by Feitnecht on copper,² which had a considerable bearing on the subject and which was of particular interest if read in conjunction with Dr. Pfeil's results.

¹ *Journal of the Iron and Steel Institute*, 1927, No. I. p. 483.

² *Zeitschrift für Electrochemie*, 1929, vol. xxxv. p. 142.

This paper was also discussed at the Additional Meeting held at Sheffield on May 15, 1929.

Mr. G. W. USHERWOOD (Sheffield) said a lot of work had been done recently on the problem of the existence or otherwise of solid solution between magnetite and ferrous oxide. The method employed by the author appeared to ensure that equilibrium was attained between the two oxides. He was surprised to find the range of solid solution extended from ferrous oxide (77.7 per cent. Fe) to an oxide having the composition 89 per cent. Fe_3O_4 and 11 per cent. Fe_2O_3 (72 per cent. Fe). The evidence at present in the literature on the relationship between magnetite and ferrous oxide was conflicting. For instance, Groebler and Oberhoffer¹ showed from the decomposition curves of ferric oxide by CO and CO_2 mixtures at various temperatures (750° to 1000° C.) that there was solid solution between Fe_3O_4 and FeO. But when the various oxides formed by that method were examined by X-rays, they found that the X-ray evidence disproved the decomposition curve, and that Fe_3O_4 could only dissolve 5 per cent. of FeO, and FeO could dissolve 39 per cent. of Fe_3O_4 . Again, Wyckoff and Crittenden² had previously shown by X-ray evidence that no solid solution existed between Fe_3O_4 and FeO, and they and McCance,³ by evidence obtained from microscopic examination of various oxides containing Fe_3O_4 and FeO, found a eutectic between Fe_3O_4 and FeO. One reason why the X-ray evidence failed to prove the existence of solid solution between Fe_3O_4 and FeO was, it seemed to him, that unless the oxides used had been extremely slowly cooled a homogeneous structure would not be obtained, and, instead, zoned crystals of Fe_3O_4 and FeO would be present, which would give rise to the results obtained by X-ray examination. To obtain homogeneous specimens of an antimony-bismuth alloy, which system formed a continuous series of solid solutions, it was well known that long periods of annealing or slow cooling (2 to 3 weeks) were required, otherwise the microstructure would show zoned crystals of antimony and bismuth. By microscopic examination of iron scales, having compositions lying between Fe_3O_4 and FeO, he himself had found zoned crystals of magnetite, the structure being developed by etching for 3 or 4 sec. with concentrated HCl. It would be interesting to see the results of an X-ray examination of the scales used by the author, in view of the fact that equilibrium appeared to have been obtained.

Mr. T. G. ELLIOT (Sheffield) was particularly interested in the effect of oxidation on the alloy steels. One got the notion, evidently wrongly, that an alloy steel, in which the chromium, nickel, and iron were in solid solution, would behave more or less homogeneously—that is, like

¹ *Stahl und Eisen*, 1927, vol. xlvii., Nov. 24, p. 1984.

² *Journal of the American Chemical Society*, 1925, vol. xlvii., July-Dec., p. 2876.

³ *Journal of the Iron and Steel Institute*, 1918, No. I. p. 239.

a simple metal—and that if the surface were oxidised and the products of oxidation examined the iron, nickel, and chromium would be found in approximately the same relation as they originally existed in the steel. Dr. Pfeil had found that that was not the case, and that the different layers had each a separate composition; from their compositions it was clear that oxidation of the metallic constituents of an alloy did not proceed at the same rate in each case.

Recently, he had met with an instance in which the metallic constituents of an alloy of nichrome composition were differentially attacked by fused alkaline salts. The metal which had been in contact with the fused salts was afterwards analysed, when it was found that the nickel had increased from 58 to 82 per cent., the chromium had decreased from 12 to 1·5 per cent., and the iron from 26 to 11 per cent. Evidently the nickel had resisted attack, whereas the greater part of the chromium and much of the iron had been removed. It was interesting to find that the chromium and iron could be removed in that manner from the solid solution with nickel.

Dr. Pfeil's explanation of the mechanism of oxidation of iron and steel was very interesting, and though he (Mr. Elliot) found it difficult to visualise the iron diffusing outwards through the scale, yet that conclusion seemed warranted from the facts stated by Dr. Pfeil.

The CHAIRMAN (Professor C. H. Desch, F.R.S.) remarked that the work, when carried forward, would lead to very important conclusions. He had no doubt that a full explanation of the effects had not been arrived at yet. The facts Dr. Pfeil had already established should throw an entirely new light on the process of oxidation at high temperatures. It might also have something to do with oxidation at somewhat lower temperatures. In the laboratory at Sheffield University they had lately investigated a process of oxidation of copper at atmospheric temperatures over rather a long period. The particular specimens examined had been corroding now for 5500 years—they came out of the excavations at Ur—and when those very ancient coppers were examined they were found to be coated with scale. As a rule there was very little metal left in the centre. Instead of the oxide changing gradually in properties from the outside to the inside it was always made up of layers, perfectly crystalline, but sharply marked off from one another. The phenomenon had seemed somewhat puzzling, but now that Dr. Pfeil had done that work on oxides he thought that his (Dr. Pfeil's) results would help them to interpret even such a different phenomenon.

CORRESPONDENCE.

Professor C. BENEDICKS (Hon. Vice-President) and Mr. H. LÖFQUIST (Stockholm) wrote: Supposing the temperature-concentration diagram for a binary system *A-B* to be known, it is easy to indicate the different

zones which will appear in a specimen, the composition of which is at the one end *A* and at the other end *B*, on account of the mutual diffusion of the elements, taking place at a temperature *T*. A horizontal line corresponding to *T* at once shows the different layers which will appear. This may be said to be the principle for obtaining all intermediate phases in binary alloys introduced by Le Chatelier,¹ and named "filiation" by Le Gris.²

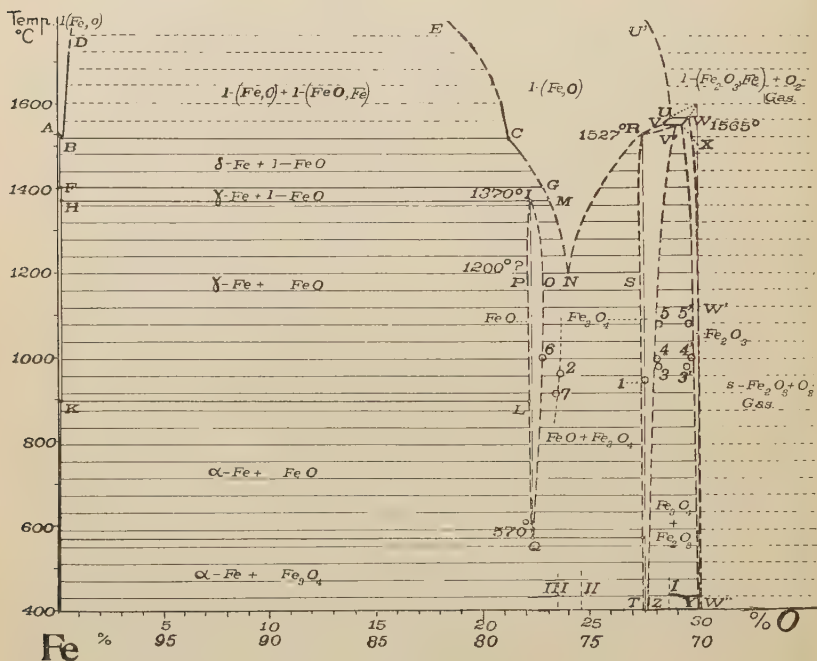


FIG. A.

An iron-oxygen binary diagram, of at least a qualitative character, has been worked out by the present writers³ (see Fig. A). The diagram shows that progressive oxidation at, say, 1000° C. gives rise to three different layers of oxide, corresponding to Fe_2O_3 , Fe_3O_4 , and FeO . The curves limiting these homogeneous regions, however, have

¹ *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1900, vol. vi. p. 365; *International Association for Testing Materials*, New York Congress, 1912, vol. ii., Part 2, No. 8, II₁₂.

² *Revue de Métallurgie, Mémoires*, 1911, vol. viii. p. 613.

³ *Zeitschrift des Vereines deutscher Ingenieure*, 1927, vol. lxxi. p. 1576; *International Congress for Testing Materials*, Amsterdam, 1927, p. 265.

only been computed. Hence, there is considerable interest in using the quantitative results obtained by the author to check the diagram.

Experiment No. 1 (p. 510), at 950°C ., was made on a heterogeneous mixture which contained ultimately 72.5 per cent. of iron. The diagram requires the formation of a single phase, Fe_3O_4 , represented by point 1 (see Fig. A). The experiment entirely verified this. Similarly, experiment No. 2 gave practically a homogeneous phase, with an iron content of 76.4 per cent. (point 2). This is slightly to the right of the homogeneous FeO region of the diagram, and indicates—as do some other observations by R. Schenck—that the boundary line OQ should actually be displaced to the right (as shown by the dotted line through 2). This result is supported by the experiments in Table V. The first value obtained, 76.5 per cent. of Fe , must approximate to the homogeneous FeO phase (saturated with oxygen), and has been indicated as point 7.

The fact that the above experiments pertain to the homogeneous regions Fe_3O_4 and FeO respectively, however, by no means justifies the conclusion drawn by the author that any oxide mixture, the average iron content of which exceeds 72 per cent., will be homogeneous (p. 511). Quite a number of intermediate determinations would be necessary in order to support that conclusion; a region of immiscibility between the FeO and the Fe_3O_4 phases is actually demonstrated by the fact that a eutectic structure exists between them (compare point N ; Oberhoffer and d'Huart; Wyckoff and Crittenden).

Experiments 3, 4, 5 support the existence of the region of immiscibility between the Fe_2O_3 and the Fe_3O_4 phases (see points 3, 3'; 4, 4'; 5, 5'); these observations are probably the first direct quantitative determinations made here. Only small adjustments of the curves $V'Z$ and XY , as assumed by the present writers, are necessary.

A further check on the diagram might be obtained by means of the experiments on p. 515. An iron phase would be in equilibrium with an FeO phase containing 77.3 per cent. of Fe . This observation, plotted as point 6, does not fit in well with the diagram; it ought to be situated on the curve PLQ (here assumed to fall to the left of the exact FeO composition). The present writers do not consider it justified to change the situation of PLQ , as even an extremely slight oxygen leakage will deform the figure obtained in this case. As a matter of fact, the author guards himself against the accuracy of these observations.

Regarding the dissociation pressure of a mixture of FeO and Fe_3O_4 , the author expresses the opinion that the pressure would be that of the higher oxide, Fe_3O_4 (p. 512). This assertion might easily give rise to a misunderstanding. As a matter of fact, when FeO and Fe_3O_4 are in equilibrium, the common dissociation pressure is *that of Fe_3O_4 saturated with iron*, being equal to that of *FeO saturated with oxygen*. Similarly, when Fe_3O_4 is in equilibrium with Fe_2O_3 , the dissociation pressure is that of Fe_2O_3 saturated with iron, identical with that of

Fe_3O_4 saturated with oxygen. The fact that the oxygen pressure, consequently, varies discontinuously between Fe and Fe_2O_3 —continuous curves only existing for the homogeneous phases (Fe, FeO, Fe_3O_4 , Fe_2O_3)—in no way precludes the possibility of effective diffusion of oxygen or of iron, as might possibly be supposed.

In the same way as the binary equilibrium diagram demonstrates the consecutive pure iron oxide layers formed, a ternary diagram, for, say, Fe-Mn-O, would show the different oxide phases and their compositions.

The determinations of the distribution of an alloyed element, say Mn, are extremely interesting. Such determinations—when available in sufficient number—will constitute a practical means of establishing such diagrams.

It must be recognised that the knowledge of the consecutive oxide layers formed does not necessarily imply a knowledge of the way in which the scale will split up mechanically. The observation made by the author regarding the appearance of three strictly different layers is interesting, but is not easy to explain even by means of the equilibrium diagram.

The mean composition of the three layers as given in Table I. have been marked in the diagram (lines I, II, III, Fig. A). As will be seen, layer I corresponds to Fe_3O_4 plus a certain amount of Fe_2O_3 . Layer III corresponds to the oxygen-saturated FeO phase (compare point 7), while layer II must be a mixture of this phase plus Fe_3O_4 . Some unpublished observations made by one of the present writers have given evidence of a dividing-up of the scale into two very distinct layers, separated by an empty space (which might be due partly to gas evolution, and partly to the considerable volume increase of the oxide). Now, the inner layer adjacent to the iron core was found to be well crystallised, and was considered to be practically pure FeO saturated with Fe; this corresponds to the author's layer III. Further, the outside compact layer was assumed to be essentially Fe_3O_4 containing some free Fe_2O_3 —that is, practically coinciding with layer I. If the empty space observed between the two layers mentioned were filled up with the $\text{FeO} + \text{Fe}_3\text{O}_4$ phases, the occurrence of the three layers observed by Dr. Pfeil would be plain; the question is how this filling-up takes place.

The very beautiful crystalline deposits obtained by the author at different rates of oxidation are assumed by him to be homogeneous. It is necessary to point out that from the external appearance it is very difficult to distinguish between crystals of FeO and crystals of Fe_3O_4 , as both crystallise in the regular system. Consequently, it cannot be considered as proved that these crystals represent one homogeneous phase—entirely contrary to the diagram, which, as has now been shown, is well supported by the previous quantitative determinations by the author.

The author is to be congratulated on taking up in such an original

way this matter of the mechanism of scale formation, and on having demonstrated that the scale formation implies a diffusion of iron as well as of oxygen—by far the most probable assumption—and not of oxygen alone, as seems to have been generally considered previously.

Dr. J. M. FERGUSON (Glengarnock) wrote: Contrary to the views expressed on p. 502, the paper is of considerable practical interest, because of the data given concerning the nature of the final products of iron and steel oxidation. Observations on the scales of commercial steels confirm the facts recorded with regard to their straticulate appearance under the microscope and general composition.

Certain conclusions reached, however, warrant further consideration, because in the study of the complex reactions involved the nature of the initial mechanism of disintegration is of the utmost importance, and this may be obscured by intermediate reactions, which occur before the ultimate products are formed.

Thus, on p. 505 it is stated that the composition of the deposits of scale layers on carbon steel is independent of the temperature and time of oxidation. In steel scales, Fe_2O_3 , Fe_3O_4 , and FeO exist in a state of intersolubility in the presence of carbon, and the composition of the first-named scale at a given temperature must depend upon the dissociation pressures of the respective oxides. Even at quite low temperatures (500° to 600°C.) the noticeably higher pressure of Fe_2O_3 in presence of carbon indicates that the oxidation of carbon steel must differ in mechanism from that of pure iron, and the nature and composition of the resulting scales must depend upon the temperature of formation and the time-temperature gradient during cooling. This is verified in practice, as at comparable rolling temperatures scale from high-carbon steel ingots is detached as thin brittle flakes of lower Fe_2O_3 content than scale from low-carbon steel which shows a lower fusion point and a tendency to stick to the rolls.

On p. 508 reference is made to the possibility of the transfer of oxygen molecules to the iron/iron-oxide interface, consequently the diffusion hypothesis lacks definition with regard to the nature of the oxygen transfer. Further, any such hypothesis must also adequately explain the mechanism of oxidation at steel-making temperatures considerably in excess of those covered by the experimental data in the paper. Recent researches¹ have established that the solubility of oxygen in iron increases with a rise of temperature, so that the dissolved oxygen must be present as a compound and not as a gas. The possibility of gaseous oxygen transfer at high temperatures could therefore be disregarded, with some gain in clarity.

Table II. contains information of value, not only for the light thrown upon the problem of resistance of steels to heat, but also upon

¹ C. H. Herty, jun., and J. M. Gaines, jun., "Effect of Temperature on the Solubility of Iron Oxide in Iron," *American Institute of Mining and Metallurgical Engineers, Technical Publication No. 88*, 1928.

a subject not mentioned in the paper—namely, the influence of scale composition on the problem of the weldability of steels. In this latter connection a scale of low fusion point seems desirable. It is interesting to note that the chemical analyses of steel scales show that apparently maximum liquation among the constituents of the metal to the outside scale layers in steel ingots occurs in the case of the oxidation products of phosphorus. Further research on this matter along the lines of the present paper would be of practical interest.

Dr. PFEIL replied that he was very pleased that Professor Carpenter had found the counter-current diffusion hypothesis acceptable on the evidence available. A great deal remained to be done before a complete understanding of the process of oxidation in iron and steel could be reached. A thorough investigation of the constitution of a section of the iron-oxygen system was required, and he proposed to attack that problem with the aid of X-rays and by the microstructure. Investigations had already indicated that the system was complicated and that important changes in phase occurred on cooling. Preliminary work had shown that it was possible to retain the high-temperature phases by quenching, and that should supply a means of investigating the high-temperature constitution.

He was grateful to Mr. Ulick Evans for his helpful contribution, but he found it difficult to follow Mr. Evans' argument in connection with the "theoretical composition" of oxide layers. In all cases, the composition of the surface scale must tend to approach equilibrium with the oxygen pressure in the atmosphere, but always containing less oxygen than the "equilibrium concentration," while the oxide in contact with the metallic base must tend to approach equilibrium at the other extreme (oxide in equilibrium with metal), but always containing more oxygen than "equilibrium composition." Clearly, the scale could in no place contain more oxygen than that required for equilibrium with the atmosphere. He thought it was probable that all metallic oxides formed solid solutions, although, no doubt, in some cases only over a very small range of composition. The oxygen concentration at the surface of the scale would then vary with the oxygen pressure in the atmosphere, and the rate of oxidation would vary accordingly. Thus, while the variation in the rate of oxidation with oxygen pressure might be too small for measurement in many cases, the principle would be common to all. It seemed to him that the only difference between the two cases cited by Mr. Evans was the choice of a standard for comparison. In the one case the equilibrium composition between oxide and metal was taken, and in the other the equilibrium between oxide and atmosphere. The vital difference between the mechanism for the oxidation of iron suggested by him (Dr. Pfeil), and that suggested by Pilling and Bedworth, was that, according to the former explanation, the scale expanded by the movement outwards of minute units (atoms or molecules), while

according to the latter explanation the scale was forced outwards bodily by the expansion.

In reply to Mr. Usherwood, Dr. Pfeil stated that he attributed the conflicting evidence of X-ray workers on the iron-oxygen system largely to the effect of changes occurring in the system on cooling. The solubility of Fe_3O_4 ¹ in FeO increased rapidly with rise in temperature, and Fe_3O_4 was deposited again on cooling. In addition, certain other changes occurred in the solid state, the exact nature of which was still uncertain. The rate of cooling had an important influence on those changes, and various structures were to be obtained at the ordinary temperatures by variations in quenching temperature and quenching rate. He (Dr. Pfeil) was bound to admit that his conclusion regarding a continuous series of solid solutions from FeO to Fe_3O_4 has not been strengthened by further investigation, and he now thought that it was extremely probable that an incorrect explanation of the reactions between scales of varying composition had been given in the paper. In particular, the microscope showed beyond possibility of doubt that at least three phases, containing 70, 72, and 74 to 78 per cent. of iron respectively, could exist, both at ordinary and at higher temperatures. The argument used in the paper involved the assumption that only one phase existed between 70 and 72 per cent. of iron, in accordance with Sosman and Hostetter's conclusions. The true explanation of the results of experiments 3, 4, and 5 (pp. 511 and 512) therefore probably lay in the existence of two phases between the range of composition 72-70 per cent. of iron. Thus, when equilibrium was reached, the scale richer in iron consisted of the " Fe_3O_4 " phase saturated with oxygen, while the oxygen-rich scale consisted mainly of the oxygen-rich " Fe_2O_3 " phase saturated with iron, plus a small amount of the " Fe_3O_4 " phase saturated with oxygen. Some remarks on experiments 1 and 2 (pp. 510 and 511) were made below in reply to Professor Benedicks.

Mr. Elliot appeared to have concluded that the varying composition of the scale layers indicated that the oxidation of the constituents in alloy steels proceeded at different rates. He (Dr. Pfeil) did not think that view was correct. It was true that nickel steels retained the nickel in the metallic form in the scale, but there was no concentration of nickel in the unoxidised steel core. Chromium and other elements with a greater affinity for oxygen than iron did not appear to oxidise at a greater rate than the iron. He held the view that the concentration of certain elements in the innermost scale layer was due to segregation after oxidation, not to preferential oxidation. The changes in composition of nichrome during heating in a salt bath were very interesting, but might be due to differential chemical solution and not be directly connected with the problem of oxidation.

He was very interested to hear Professor Desch's observations on

¹ The terms FeO , Fe_3O_4 , and Fe_2O_3 are used here to indicate solid solutions approximating in composition to these compounds.

the layer-like oxide deposit on copper. He had no real reason to expect the oxidation of other metals to proceed by the same mechanism as iron; it seemed possible that there might be several mechanisms of oxidation, but it was possible that the oxidation of copper and iron occurred by the same mechanism.

He was extremely grateful for Professor Benedicks and Mr. Löfquist's very helpful contribution. He thought that their diagram was to a large extent correct. He thought, however, that the line *OQ* would have to be displaced even more to the right than the dotted position (2, 7), so as to pass through a point near 1000° C., 75 per cent. Fe. He saw no reason why the point 7, representing the iron content of a scale produced under conditions of very low oxygen pressure, should consist of the FeO phase saturated with oxygen (Table V., specimen 3); it was much more probable that specimen 44 (Table V.), containing 75 per cent. of iron, consisted of the FeO phase nearly saturated with oxygen.

Professor Benedicks' criticism with regard to the conclusions drawn from the two experiments on pp. 510 and 511 was justified by the fact that further investigation seemed to confirm the existence of the break in the series found by some other workers. It was necessary to repeat, however, that several experiments were carried out in which equilibrium was reached at about 74 per cent. of iron in the two scales, indicating that the FeO solution extended to 74 per cent. of iron at 1000° C.

Experimental investigation into the solubility of Fe in FeO was extremely difficult. Professor Benedicks suggested that the results obtained might be low, due to oxygen leakage, but he (Dr. Pfeil) thought that there was a greater likelihood of obtaining results which were too high. Results obtained by analysing scale which had been heated for prolonged periods in contact with iron *in vacuo* showed iron contents in the scale ranging from 77.3 to 89.3 per cent. The high results were definitely not due to the entrance of reducing gases during the experiments, since there was no loss in weight. The high iron scales contained metallic iron in a form which could scarcely have been precipitated from solution on cooling, and which was not retained in solution by quenching. The high results were finally traced to the reduction of FeO by metallic iron. The apparent absurdity of this statement was removed when it was borne in mind that the dissociation pressure of FeO decreased with decrease in temperature, and hence, if the metallic iron were cooler than the FeO, the FeO might be reduced and the iron oxidised. It had been found that when the time of heating was very long (1 to 2 weeks) an extremely small temperature variation was sufficient to cause the oxygen exchange to proceed to an appreciable extent. When the most careful precautions were taken to avoid a temperature gradient in the working portion of the furnace, the highest, but not necessarily the most accurate, figure obtained in the scale after heating in contact with iron for 14 days *in vacuo* at 1000° C. was

78 per cent. of iron. That figure agreed well with Professor Benedicks' diagram.

Professor Benedicks took exception to the statement on p. 515 that the dissociation pressure of a mechanical mixture of Fe_3O_4 and FeO would be that of the higher oxide. It was important to point out that in the paper that statement was prefaced by the words "If it be assumed that no intermediate phase between Fe_3O_4 and FeO can exist"; in other words, if FeO and Fe_3O_4 did not form solid solutions. He (Dr. Pfeil) agreed entirely with the statements Professor Benedicks made with regard to equilibrium between two solid solutions.

Definite evidence of the relation between the three-layer formation in the scale and the three-phase constitution of the system was now available. The outer layer consisted of the two solid solutions " Fe_2O_3 " and " Fe_3O_4 ." The middle and innermost layers in pure iron-oxygen scales consisted of the " FeO " solid solution, homogeneous at high temperatures and retained homogeneous by quenching, but splitting up into a duplex structure like that of 60 : 40 brass on cooling. Thus, the division between the middle and innermost layers was mechanical and not chemical. Since the middle layer contained 75.5 per cent. of iron, those facts might be taken as further evidence of the necessity for moving the line OQ farther to the right.

Professor Benedicks referred to a very interesting case of a two-layer scale deposit, the two layers being separated by a space, and the inner layer showing a crystalline surface. He (Dr. Pfeil) had often met with similar examples when large, flat specimens were oxidised. The phenomenon was due to a loss of contact between scale and iron at a late stage in the oxidation. If a piece of Armco iron, 6 in. \times 2 in. \times $\frac{1}{4}$ in., were cleaned on one face by filing or grinding and then oxidised at 1000° to 1050° C. in a muffle free from excessive draughts, oxidation proceeded normally for one to two days; then the scale already formed rose gradually, due probably to expansion stresses, forming one large unbroken blister. Those two stages were illustrated in Figs. B and C (p. 559). Further oxidation of the iron could only occur by oxygen dissociating from the inner face of the scale. Thus, the iron was slowly oxidised under very low oxygen pressure, and crystalline scale was produced on the metal, as indicated in Fig. D.

Polished and etched sections through crystalline scale deposits showed that in all cases they consisted of a single phase when quenched from the temperature at which they were produced, but that if slowly cooled they consisted of crystallites set in a ground-mass of a second phase.

He was gratified that Dr. Ferguson had found the paper of practical interest. He was very interested in Dr. Ferguson's remarks on the varying behaviour of the scale during rolling, according to the carbon content of the steel. He (Dr. Pfeil) found that whatever the carbon content of the steel, the scale deposit had the three-layer character. It was possible that the outer layer, consisting of oxygen-rich phases,

decreased slightly in relative thickness with increase in the carbon content of the steel, but he had not detected that variation, nor had he found any variation in the analysis of the individual layers with different carbon contents. He thought it desirable to point out, how-

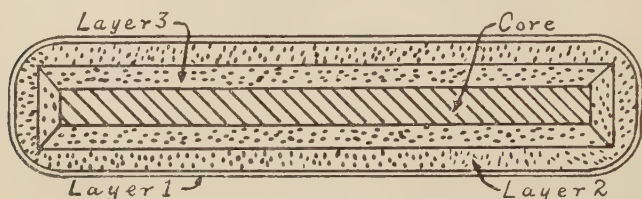


FIG. B.



FIG. C.

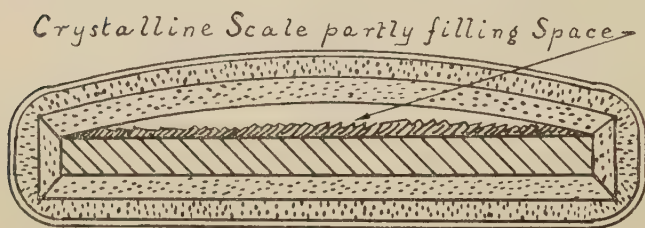


FIG. D.

ever, that in most of his experiments oxidation had been allowed to proceed for several days before the separation and analysis of the scale layers. The rate of oxidation was slow when the protective scale deposit was thick, and when the rate of oxidation was slow decarburisation proceeded more rapidly than the oxidation, so that in many instances the metal surface in contact with the scale was very low in carbon, although the centre of the metal was still high in carbon.

THE DIFFERENTIAL METHOD FOR MEASURING THE THICKNESS OF HARD CASES WITHOUT SECTIONING THEM.*

By EDWARD G. HERBERT, B.Sc., M.I.MECH.E.,

AND

PAUL WHITAKER (MANCHESTER).

THE problem of determining the thickness of the case on case-hardened steel without cutting or breaking through it is one that has exercised many minds, and by some has been deemed insoluble. The most natural way of approach to this problem is through the hardness test, but any hardness test, depending, as most of them do, on penetration of the surface by an indenter, merely gives a false reading on case-hardened work—a reading, that is to say, which is liable to be influenced by three variables, namely, the hardness and the thickness of the case, and the hardness of the core, but which fails to discriminate or to determine any one of them. A low Brinell reading on case-hardened steel may denote a soft case or a thin case, or one which is both soft and thin, but the test is incapable of measuring either hardness or thickness. The essential difficulty of the problem arises from the existence of the above-mentioned three variables, and from the impossibility of determining more than one variable by a single measurement.

The method to be described consists in making two different hardness tests, a primary test which measures only one variable, the hardness of the case, and a secondary test which measures the combined effect of two variables, hardness and thickness of case. The difference between the two hardness readings is a function of the second variable, thickness of case. The third variable, hardness of core, may, without serious error, be treated as a constant for any given variety of steel.

The two hardness tests used in the differential method are the pendulum time test and the Brinell test.

* Received January 3, 1929.

Primary Hardness Test.—The time test made with the Herbert pendulum hardness tester measures the surface hardness, and is unaffected by hardness below the surface. This arises from the fact that the 1-mm. steel ball used in the pendulum makes no permanent indentation in very hard steel, the time of swing by which the hardness is measured being a function of the radius of curvature of the elastic depression caused by the pressure of the ball, and in which the ball rolls. It is thus possible to measure hardness gradients by steps of 0.0005 in. or less by honing away the surface and making successive hardness tests. This method of measuring hardness gradients has been described and illustrated.⁽¹⁾

Experiments have shown that true hardness readings are obtained with the pendulum on hard steel plates of any thickness down to 0.1 mm. (0.004 in.), when the plates are supported on soft mild steel, and true readings would be obtained on even thinner hard layers if integral with the soft core, as in case-hardened steel. In testing commercially case-hardened steel it may therefore be taken as strictly accurate that the pendulum reading is unaffected by the thickness of the case.

Secondary Hardness Test.—The Brinell hardness number of a case-hardened specimen depends on the hardness and thickness of the case, and, especially if the case is very thin, on the hardness of the core. The effect of the Brinell test (10-mm. ball, 3000-kg. load) on steel having a case 0.5 mm. thick is shown in Fig. 4 (Plate LXIII.). The case is pressed into the core, but it offers considerable resistance to penetration, the resulting hardness number being higher than that of the core by an amount which is nearly proportional to the thickness of the case. Annular cracks are usually found in the impression, but they do not seriously interfere with the measurement of its diameter.

Fig. 5 is a section through a Brinell impression in steel which had been case-hardened to a depth of 1.3 mm. The case is pressed into the core to a slight degree and the surface is unbroken, but a conical fissure is created below the impression, and this opens when the load is removed, owing to the elastic recovery of the hard surface.

A Brinell test on a still thicker case does not crack it, but the surface of the specimen is seen to be slightly concave around the impression, showing that there has been some yielding of the

core, and the hardness number is lower than it would have been if the steel had been hard throughout.

Experiments were made with specimens of Ubas steel, which were carburised in boxes for various periods, quenched at 900° C. in cold water, reheated, and quenched at 780° C. The specimens were tested for hardness by the pendulum time test and by the Brinell test, the latter being made with a 10-mm. steel ball and a 3000-kg. load, and with a 5-mm. ball and a 750-kg. load. The specimens were sectioned by grinding, polished, and etched, and the thickness of case was measured under the microscope. The core hardness was measured by the Brinell method, and was found to be 228.

The pendulum tests were made with a 1-mm. steel ball in the 4-kg. pendulum, and the time hardness numbers were converted into Brinell numbers by the formula,

$$B = 10T,$$

where B is the Brinell number and T the pendulum time hardness number. The tests could equally well have been made with the 1-mm. diamond in the pendulum, the conversion factor in that case being 13·5.

The Brinell hardness number of each specimen was subtracted from the corresponding converted pendulum number; the resulting differences are given in Tables I. and II., and are plotted against the thickness of case in Figs. 1 and 2.

TABLE I.—*Pendulum Time and Brinell Hardnesses.*

Brinell Test : 10-mm. ball, 3000-kg. load.

Specimen No.	Pendulum Time Hardness $\times 10$.	Brinell Number.	Difference. $10T - B$.	Thickness of Case. Mm.
9	706	277	429	0·127
4	707	321	386	0·5
5	708	364	344	0·55
3	717	351	366	0·7
1	736	515	221	1·0
7	723	515	208	1·2
6	697	495	202	1·3
14	684	633	51	2·2
8	663	666	0	2·4
10	671	666	5	2·9
13	626	627	0	3·0

TABLE II.—*Pendulum Time and Brinell Hardnesses.*

Brinell Test: 5-mm. ball, 750-kg. load.

Specimen No.	Pendulum Time Hardness $\times 10$.	Brinell Number.	Difference. $10T - B$.	Thickness of Case. Mm.
9	706	337	369	0.127
4	707	513	194	0.5
5	708	474	234	0.525
3	717	591	126	0.7
1	736	699	37	1.0
7	723	720	3	1.25
8	663	667	0	2.4

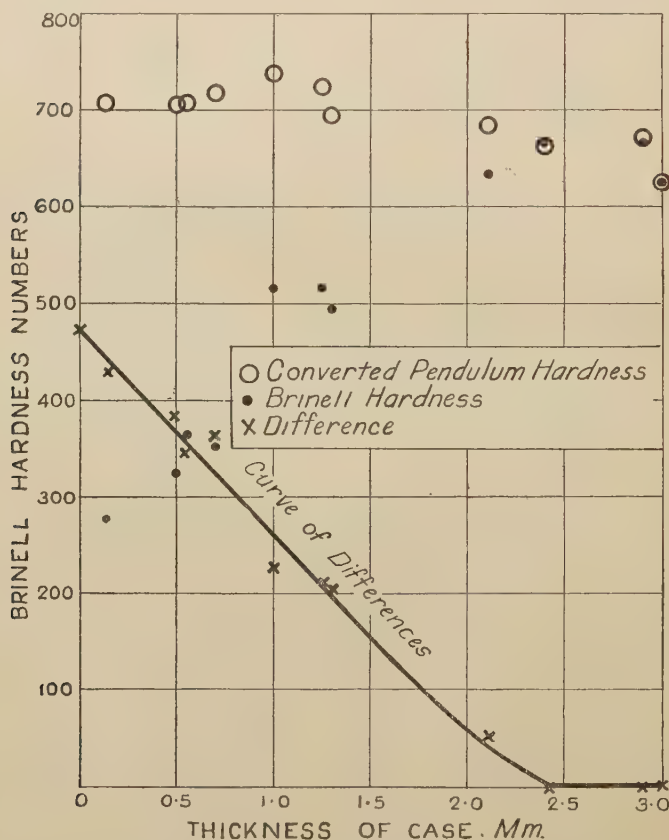


FIG. 1.—Differentials and Thickness of Case. Primary test: Pendulum time hardness converted to Brinell. Secondary test: Brinell hardness (10-mm. ball, 3000-kg. load).

A specimen with an infinitely thin case of hardness 700 Brinell would obviously give a Brinell reading equal to that of the core,

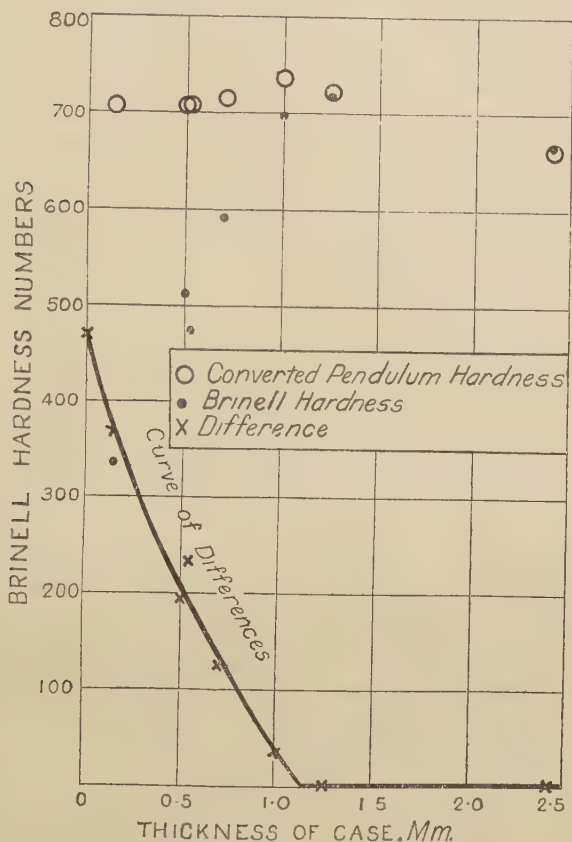


FIG. 2.—Differentials and Thickness of Case. Primary test: Pendulum time hardness converted to Brinell hardness. Secondary test: Brinell hardness (5-mm. ball, 750-kg. load).

228, since an infinitely thin case would not affect the Brinell test. Thus the point where the curves of differences in Figs. 1 and 2 cut the axis of ordinates is $700 - 228 = 472$. Starting from this point, the curve of differences is seen to be nearly a straight line, cutting the horizontal axis at a point corresponding to the

minimum thickness of case for zero difference between the two hardness readings. This thickness is 2.4 mm. when the Brinell test is made with a 10-mm. ball and 3000-kg. load, and 1.15 mm. with a 5-mm. ball and 750-kg. load. On thicker cases the respective Brinell tests gave the true hardness, and the difference between the converted pendulum and the Brinell readings was zero.

Thus the differential gives a clear and consistent indication of the thickness of the case. The secondary test with a 5-mm. ball is only capable of *measuring* case thicknesses up to 1.15 mm., but a zero differential indicates a case of *not less* than 1.15 mm., which would be sufficient for most commercial work. The 5-mm. ball Brinell test will often be preferred, because the impression is small and does not seriously deface the work, while the range of thicknesses it is capable of measuring covers general commercial practice. The 10-mm. ball with 3000-kg. load can be used to measure thicker cases up to 2.4 mm., and still thicker cases can be measured by using a heavier load.

Table III. gives thicknesses of case corresponding to various

TABLE III.—*Differentials and Case Thicknesses. Ubas Steel.*

Thickness of Case.		Differential. 10T - B, or 13.5D - B.		Thickness of Case.		Differential. 10T - B, or 13.5D - B.	
Mm.	In.	Brinell, 10-mm. ball, 3000-kg. load.	Brinell, 5-mm. ball, 750-kg. load.	Mm.	In.	Brinell, 10-mm. ball, 3000-kg. load.	Brinell, 5-mm. ball, 750-kg. load.
0.1	0.004	450	390	1.4	0.055	174	0
0.2	0.008	430	330	1.5	0.059	151	...
0.3	0.012	407	288	1.6	0.063	133	...
0.4	0.016	386	245	1.7	0.067	115	...
0.5	0.020	364	200	1.8	0.071	96	...
0.6	0.024	341	170	1.9	0.075	78	...
0.7	0.028	321	135	2.0	0.079	59	...
0.8	0.032	300	100	2.1	0.083	42	...
0.9	0.035	276	65	2.2	0.086	26	...
1.0	0.039	256	33	2.3	0.090	12	...
1.1	0.043	237	10	2.4	0.094	0	...
1.2	0.047	218	0	2.5	0.098	0	...
1.3	0.051	195	0				

T = pendulum time hardness number ; 4-kg. pendulum, 1-mm. steel ball.
D = diamond time hardness number ; 4-kg. pendulum, 1-mm. diamond.

differentials for the two standard Brinell tests, and is applicable to a steel having a core hardness of 228 Brinell after quenching.

A general expression for the differential method of case measurement applicable to steels which have different core hardnesses can be found by assuming a straight line for the

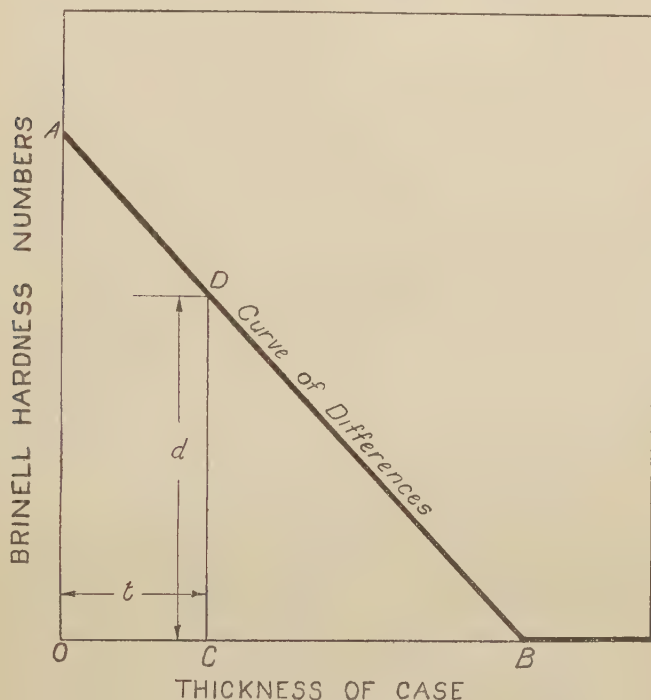


FIG. 3.—Differentials and Thickness of Case.

differential curve. In Fig. 3 let OA be the average difference between the true Brinell hardness of the case and of the core, OB the minimum case thickness for zero differential, and D any point on the differential curve corresponding to a case thickness OC .

- Let C be the converted pendulum hardness of case = $10T$, or $13.5D$;
 c the Brinell hardness of the core;
 M the minimum case thickness for zero differential;
 t the thickness of case corresponding to any point D ; and
 d the corresponding differential value.

In the similar triangles AOB , DCB ,

$$\frac{OA}{OB} = \frac{CD}{CB}$$

$$\frac{C - c}{M} = \frac{d}{M - t}$$

$$M - t = \frac{Md}{C - c}$$

$$\text{Thickness of case, } t = M \left(1 - \frac{d}{C - c} \right)$$

It will be observed that this expression takes account of all three variables, case hardness, case thickness, and core hardness, and that it contains only one constant, M , which depends on the conditions of the Brinell test, and on the core hardness of the particular steel employed. The value of M for any given steel can be found by experiment. It is only necessary to make differential tests on cases of known thickness, and solve the equation for M , taking $C - c$ as the average difference between case and core hardness in the correctly case-hardened steel.

It may be asked whether the differential method can be used with any hardness tests other than the pendulum and Brinell.

The pendulum hardness tester is, so far as the authors are aware, the only instrument capable of making measurements of surface hardness which are unaffected by the hardness below the surface, and it is therefore the only one available for the primary test, but the Brinell is not the only hardness test which gives false readings on case-hardened work ; indeed, it may be doubted whether there is any hardness tester other than the pendulum which does not comply with this essential condition for the secondary test. Penetration tests, such as the Vickers and the Rockwell, are affected by the thickness of the case, and if used with sufficient load would presumably give useful indications of any thickness of case that is likely to be met with in practice.

The only other necessary condition is that the secondary hardness test should give Brinell numbers, or numbers which can be converted to the Brinell or pendulum scale of hardness. The above formula will apply, if a suitable value is given to M .

In applying the differential method to the measurement of case thickness, one element of uncertainty exists. A local thinness may have been caused by uneven heating during car-

burisation or by inadequate covering of some part of the work with carburising material. Local thinness may also be produced in the operation of grinding. Unless, therefore, some means can be employed for exploring the whole surface of the case-hardened article, local thinness of case may escape detection. The differential method only gives the thickness at the spot or spots to which it is applied.

This element of uncertainty is eliminated by the cloudburst hardness test.^(1, 2)

The cloudburst test consists of the dropping of a very large quantity of hard steel balls from a known height. The height of fall is so chosen that steel of the desired degree of hardness when placed in the cloudburst machine is unmarked by the impact of the balls, but any areas of inferior hardness are revealed by their indented appearance. The cloudburst test complies with the conditions for the secondary hardness test in the differential method of measurement. It is affected not only by the hardness but also by the thickness of the case. For a given height of fall there is a minimum thickness of case below which the surface will be indented even though fully hardened. The cloudburst test detects not only soft spots, but also thin spots in case-hardened work.

The general conditions for testing case-hardened work by the cloudburst method are : a fall of 2 m. with balls 3 mm. in diam. Surfaces of 700 Brinell and upwards are unmarked by this test, provided that the thickness of case is not less than 0.5 mm. Thinner cases are more or less indented according to their thinness. Fig. 6 (Plate LXIII.) shows two specimens of Ubas steel which had been case-hardened and tested by the cloudburst (3-mm. balls falling 2 m.). The specimen on the left has a case 0.5 mm. thick of time hardness 70.7 (707 Brinell), and it is unmarked by the cloudburst ; that on the right is of practically the same superficial hardness, 70.6 (706 Brinell), but the thickness of the case is only 0.127 mm. (0.005 in.), and it is seen to be considerably indented by the cloudburst.

The general procedure recommended for the inspection of case-hardened work is as follows : Cloudburst the whole surface with 3-mm. balls falling 2 m. If the case everywhere has a hardness of at least 700 Brinell and is not less than 0.5 mm.

(0.020 in.) in thickness, the surface will be unmarked, and no further test is required.

If any indented areas appear, they are either thin, or soft, or both. Test such areas with the pendulum. If their time hardness is not much less than 70 (700 Brinell) the case is hard, but thin. The actual thickness of case is then measured by making a Brinell test, subtracting the Brinell number from the converted pendulum number, and referring to Table III. If the thickness of case is considered inadequate, the carburising process may be repeated.

If the pendulum shows the indented area to have a low hardness value, measure the thickness of case by the differential method, and if the thickness is found to be adequate, requeen the work.

It is proposed to apply the differential method to the measurement of thickness of cases on nitrated steel and to the thickness of chromium plating; these further developments and the use of secondary hardness tests other than the Brinell are under investigation.

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- (1) E. G. HERBERT: "Cloudburst Process for Hardness Testing and Hardening," *Paper read before the American Society for Steel Treating*, October 1928.
- (2) E. G. HERBERT: "The Work-Hardening of Steel by Abrasion, with an Appendix on the 'Cloudburst' Test and Superhardening," *Journal of the Iron and Steel Institute*, 1927, No. II. p. 265.

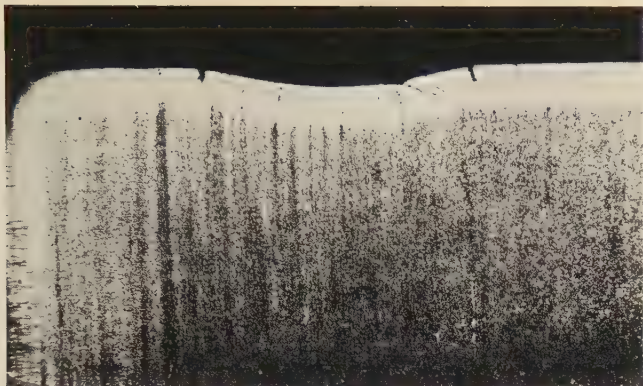


FIG. 4.—Brinell impression (10-mm. ball, 3000-kg. load) in case-hardened steel. Thickness of case 0.5 mm. $\times 10$.



FIG. 5.—Brinell impression (10-mm. ball, 3000-kg. load) in case-hardened steel. Thickness of case 1.3 mm. $\times 10$.

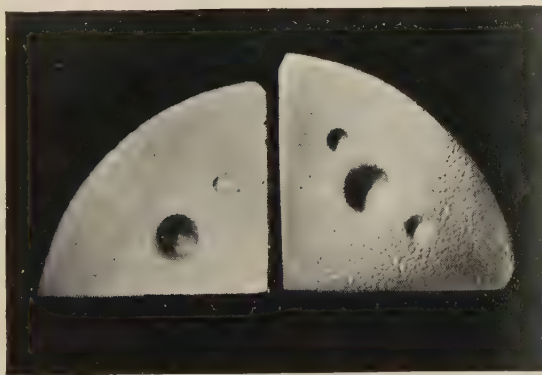


FIG. 6.—Case-hardened steel tested by Brinell and Cloudburst methods. *Left*, Case thickness 0.5 mm.; *Right*, case thickness 0.127 mm.

DISCUSSION.

Mr. DARTREY LEWIS (Bridgeport, Conn., U.S.A.) said that case-hardening was a difficult commercial process that was liable to fluctuation and needed accurate control, and hence an easy method of measuring case depth was of great practical value.

He had been associated with a firm which had been measuring case depth by measuring the magnetic properties of the case-hardened

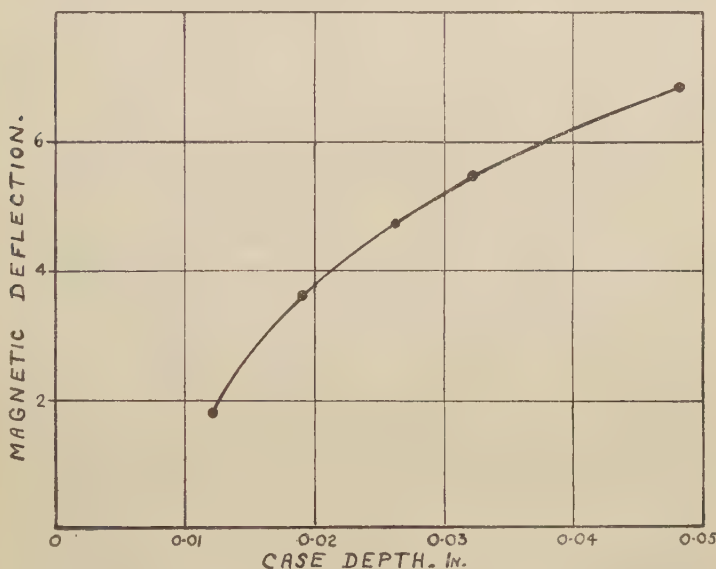


FIG. A.—Relation between Case Depth and Magnetic Deflection.

material; the method had been developed some years ago by A. V. de Forest in the United States. If a piece of wire that had been case-hardened—the core being, of course, of mild steel and the case fully-hardened quenched steel—were magnetised in a constant magnetic field the case would take up comparatively little magnetism, because it was extremely hard; on the other hand, the core would quite readily magnetise. Under constant conditions, therefore, the degree of magnetisation of such a section depended on the proportion of case to core. The apparatus used for applying that principle to measuring the case depth of carburised chains consisted of two magnetising coils, one for small sizes of chain, the other for large sizes. In the middle

was a scale, on which travelled a light spot reflected from a galvanometer, according to the depth of the case on the chain. It had been found possible to set limits on the scale between which the deflection must rest in order to get satisfactory case depth. At the top was a telephone plug, which plugged into different holes according to the size of the chain that was being tested. That apparatus was capable of testing twenty different sizes and shapes of chain. An alternating magnetic field was used, and a simple alternating current bridge was arranged so that the galvanometer deflection depended on the number of lines of magnetic force passing through the testing coil.

Fig. A showed the relationship between the deflection on the scale and the case depth. The relationship was very good, but was accurate only when the case was fully hardened. If the case were only partially quenched it became less accurate, but for commercial operation where the quenching was uniform and the carburising operation was subject to variation the magnetic method of testing was a very useful form of control. That machine had been used commercially for a number of years; at the present time it was testing as many as 4000 individual chains in 24 hr., and of course those chains were not destroyed.

Mr. T. H. TURNER (Birmingham) thought the authors' method was ingenious, but he failed to see that it was safe to use the 10-mm. Brinell test, which would produce radiating cracks in a case-hardened surface. Those who had examined Brinell indentations in case-hardened material must have come across cracks of that sort, especially in etched samples; they would not wish them to be produced in the surfaces of many types of articles.

Brearley had shown several photographs of cracks of that type, and had stated that a Brinell impression made in a hardened steel object was always a potential defect.

Mr. HERBERT, in reply, said he had not been aware of the method described by Mr. Lewis, but, while his own method would be quite inapplicable to thin wire or chain, he thought that described by Mr. Lewis would be equally inapplicable to such a thing as a big gear-wheel. Mr. Lewis' method, however, was very ingenious, and the only thing he had against it was that it did not measure both hardness and depth. In investigating case-hardened work it was necessary to know both the hardness of the case and its depth.

In reply to Mr. Turner, he said that he had applied his method to a great many case-hardened specimens, but had never met with the type of crack to which Mr. Turner had referred. In moderately thin specimens one got annular cracks, but he had never come across cracks radiating from a Brinell impression in case-hardened steel.

A METHOD FOR THE ESTIMATION OF HYDROGEN IN STEEL.¹

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AND

GUY BARR, B.A., D.Sc.

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THE usual method of estimating gases in metals is to heat the sample in a vacuum and absorb the gases or their combustion products in various reagents, as described by Jordan and Eckmann,² or else the total gas evolved is collected, and an analysis made to determine its constituents. These methods have usually been applied to metals containing a relatively small proportion of gas, and, possibly on account of the extreme difficulty of maintaining a high vacuum without leakage in a complicated piece of apparatus, very divergent results have been recorded from time to time.

The estimation of hydrogen by measuring the volume would appear to be preferable to combustion with oxygen and weighing the water formed. Also, if the hydrogen is evolved by heating without the aid of a vacuum the method can be very much simplified.

In the present case the problem was to determine whether a steel which had been in contact with hydrogen under pressure and at an elevated temperature for a considerable time contained any appreciable amount of hydrogen.

Heyn,³ using samples of mild steel which had been heated in hydrogen and quenched, determined the amount of hydrogen retained by the metal by heating it in a current of nitrogen and passing the gas through hot copper oxide, the water formed being collected in phosphorus pentoxide and weighed. He found that his determinations gave very little more than the blank test,

¹ Received February 19, 1929.

² *U.S. Bureau of Standards Scientific Paper*, No. 514, 1925.

³ *Metallographist*, 1903, vol. vi. p. 39.

although the treatment in hydrogen had apparently caused brittleness in the steel, which was removed by subsequent heating in nitrogen. He had, however, only treated his samples with hydrogen at atmospheric pressure and for a relatively short time.

As it was probable that the samples at the disposal of the present authors would contain considerably more hydrogen, it was decided to adopt the method of heating the sample in a known volume of nitrogen and measuring the volume of hydrogen evolved by means of the Shakespear katharometer.¹ The circulation of a limited volume of nitrogen minimises the effects of any impurities present in the gas, such as oxygen, &c.

The laboratory type of katharometer, in which two spirals of platinum wire are mounted in separate cells in a metal block, was used. Small brass tubes communicated with each cell, and one of these was connected to the apparatus, as indicated in Fig. 1. The other was connected to the pure nitrogen supply. The two spirals formed two arms of a Wheatstone bridge, which was completed by two manganin resistances. A constant working current of 0.12 amp. was used. A deflection type of galvanometer, which gave zero deflection with the same gas in both cells, was employed in the bridge. Arrangements were made so that the same galvanometer could be used to measure the standard current.

Description of Apparatus.—The apparatus is shown in Fig. 1. The heating tube *T*, of transparent silica, is 24 in. long and 1 in. in diam., closed at one end, and fitted at the open end with a glass cap *C*, the joint being sealed by means of a glass sleeve covered with vacuum wax.

A transparent silica delivery tube projects through the cap and reaches nearly to the closed end of the tube *T* containing the sample *S*. The other end of the delivery tube is fitted to a glass tube by means of a waxed joint *W*, and the glass tube is connected, by means of a ball-and-socket type of joint,² with the push valve *A* of a circulating pump. An outlet tube in the glass cap is connected by means of a waxed joint *W*₁ to the pull valve *A*₁ of the pump, to one tube of the katharometer, and to a large

¹ H. A. Daynes, *Proceedings of the Royal Society*, 1920, [A], vol. xevii. p. 273.

² E. I. Lewis, *Chemistry and Industry*, 1928, vol. xlvii. p. 1238.

vertical tube *B* containing mercury, which serves to keep the pressure in the apparatus constant during heating and cooling and to allow for an increase in volume due to any gas evolved from the sample. This vertical tube is fitted at the upper end with a thin glass rod *R* drawn out to a point; the point is tipped with blue glass so that the mercury can be adjusted to a con-

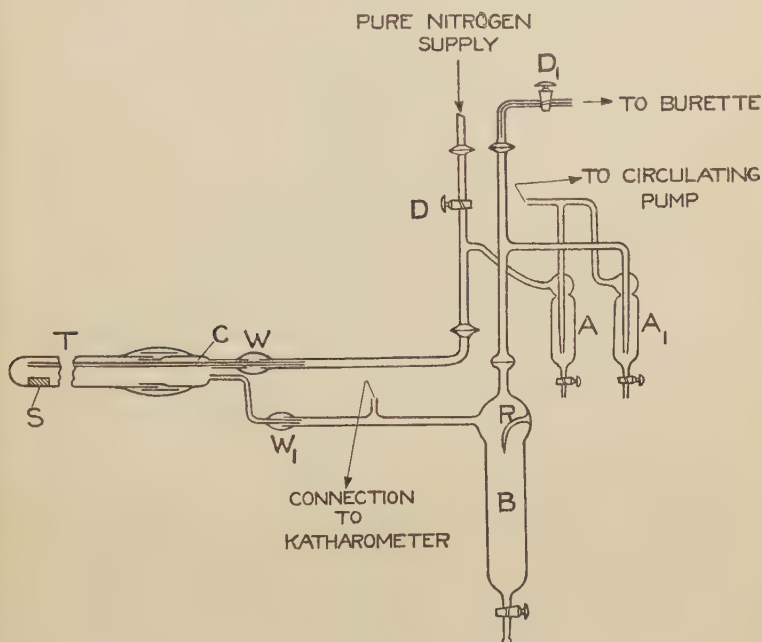


FIG. 1.

stant level. The lower end is fitted with a tap and connected to a mercury reservoir.

The push valve *A* is also connected to a tube with a tap for delivering a supply of pure nitrogen. The pull valve *A*₁ is connected to a capillary outlet tube carrying two taps *D*₁ and *D*₂, as shown in Fig. 2.

Between the taps a T-junction provides a connection to a burette containing mercury, the lower end of which communicates with a mercury reservoir. The burette can be closed at the top end by a two-way tap *D*₃, which connects, in one position, with a

manometer M for the purpose of adjusting the gas in the burette to atmospheric pressure.

The circulating pump illustrated in Fig. 3 was designed by one of the authors, and a modified form has been described elsewhere.¹ A and A_1 are valves containing concentrated sulphuric acid; the points of connection to the other parts of the apparatus



FIG. 2.

are shown (see also Fig. 1). They are connected through a common tube to one limb E of a U-tube containing mercury. The mercury in this U-tube acts practically as a piston by moving up and down, and by means of the valves A and A_1 causes the gas in the apparatus to be constantly circulated. The up-and-down movement of the mercury is obtained by means of a small pressure of water, which is admitted from the mains at K to the other limb E_1 of the U-tube, and escapes at L . A small amount of mercury is trapped in the tube at H , and this is pushed along by

¹ G. Barr, *Journal of the Chemical Society*, 1928, p. 3293.

the water in escaping to L , causing a rise of pressure and, therefore, depressing the mercury level at N and E_1 . The pressure is suddenly released as the small amount of mercury is expelled into the tube O , causing the mercury level to rise again at N and E_1 . Consequently another small amount of mercury is again trapped at H owing to the rise of the level at N sealing off the water current, and the cycle is repeated. Nitrogen could be admitted

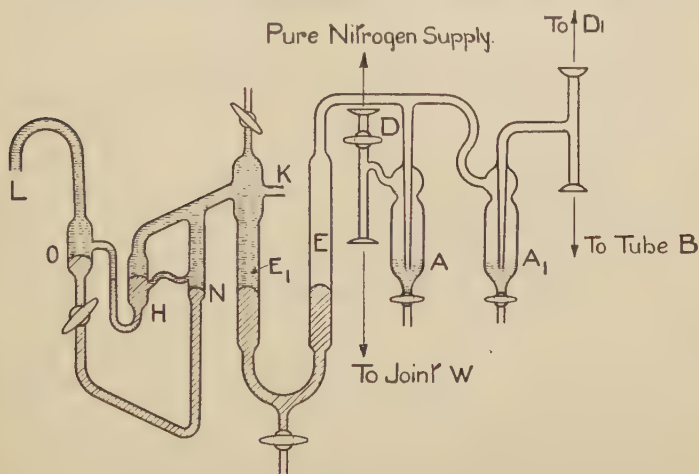


FIG. 3.

to the apparatus through the tap D and escape through taps D_1 and D_2 .

The nitrogen used was obtained from a cylinder, and was purified by passing through the following system :

- (1) A U-tube containing soda-lime, to remove carbon dioxide.
- (2) Concentrated sulphuric acid, to remove moisture.
- (3) A tube heated to 700°C . and containing first a spiral of copper gauze and next a spiral of nickel gauze, to remove the bulk of the oxygen.
- (4) Concentrated sulphuric acid.
- (5) A tube heated to about 800°C . containing pure electrolytic iron turnings.
- (6) Concentrated sulphuric acid before passing into the apparatus.

All joints on the apparatus were either made with vacuum wax or were of the ball-and-socket type.

Calibration of Apparatus.—It was necessary to know the volume of the apparatus between the taps D and D_1 . This was determined by filling with carbon dioxide, and to avoid corrections due to changes in temperature and pressure and impurities in the carbon dioxide, a glass vessel of known volume was filled at the same time. The carbon dioxide in each was then washed out with nitrogen through potash bulbs, the bulbs being weighed before and after. The volumes of the apparatus and of the standard vessel were proportional to the increases in weight obtained.

The katharometer was also calibrated by means of synthetic mixtures of pure nitrogen and hydrogen, nitrogen being used as the standard gas for comparison.

Determination of Hydrogen.—A piece of the steel was carefully cleaned, weighed, and placed in the heating tube, as indicated in Fig. 1 at S , and the cap C was sealed on with wax. With the circulating pump in action, nitrogen was then passed through the apparatus for about 2 hr. to ensure that all oxygen was washed out. The pump was stopped, the tap D closed, and the mercury levels in B and E adjusted to fiducial marks. When the pressure in the apparatus was atmospheric the taps D_1 and D_2 were closed. The pump was again started and the nitrogen passed to the standard tube of the katharometer, and the electric current was adjusted to the standard reading on the galvanometer. An electric resistance furnace, regulated to a temperature of 600°C. , was then placed in position on the heating tube.

The gas in the apparatus was retained at atmospheric pressure by lowering the mercury reservoir attached to the vertical tube B . The galvanometer was switched over to the bridge position, and the deflection caused by the evolution of hydrogen noted.

The heating was continued for some time after a constant deflection had been obtained; the period of heating was usually about 1 hr. The furnace was then withdrawn, and during cooling the gas was maintained at atmospheric pressure by raising the mercury reservoir.

When normal conditions of temperature had been restored, the deflection was noted, the taps D_1 and D_3 were opened, and

the increase in the volume of gas in the apparatus was measured by raising the mercury level in *B* to the blue point at *R* (the original level) and transferring the excess of gas into the burette; the pressure was carefully adjusted to atmospheric, as indicated by the manometer *M*, by manipulation of the mercury reservoir attached to the burette.

In Fig. 4 is shown a device for observing variations in volume due to changes in room temperature and barometric pressure

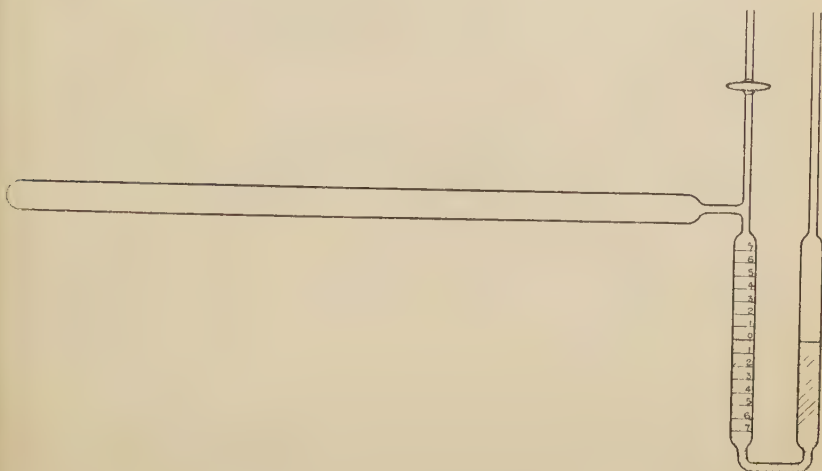


FIG. 4.

during the course of an estimation. This apparatus is placed in contact with the heating tube when the latter is not in the furnace. Its volume is known and approximates to that of the main apparatus. The tap is closed at the commencement of an estimation at the same time that the other taps are closed. Any variations in temperature or pressure are recorded on the scale, and corrections can be made to the final volume.

The method has been successfully used to estimate hydrogen in a number of samples of mild steel which had been subjected to special conditions. As the estimation of hydrogen by the katharometer would be affected by the presence of other gases, samples withdrawn from the apparatus were analysed by ordinary gas analysis methods. Only a very small amount of a hydrocarbon

gas was detected, which would not materially affect the hydrogen results.

The range of the galvanometer allowed a hydrogen content up to 10 per cent. to be measured in a total volume of 440 millilitres.

The method is very sensitive, as it is possible to detect 0.5 millilitre of hydrogen. At a temperature of about 600° C. all the hydrogen was evolved with a heating period of 1 hr. Higher temperatures up to 900° C. gave no appreciable increase in the amount, but tended to decompose the small amount of hydrocarbon gas present.

The authors desire to acknowledge the advice and encouragement received from Dr. W. Rosenhain, F.R.S., Superintendent of the Department of Metallurgy and Metallurgical Chemistry at the National Physical Laboratory.

ANNUAL DINNER.

THE Annual Dinner of the Institute was held in the Grand Hall, Connaught Rooms, London, on May 2, 1929, under the Chairmanship of Professor Henry Louis, M.A., D.Sc., President. There was a large attendance of members and guests, among whom were the Rt. Hon. Viscount Falmouth; Sir Philip Cunliffe-Lister, K.B.E., M.P., President of the Board of Trade; Sir Charles A. Parsons, C.B.E., O.M., F.R.S. (Bessemer Medallist); Colonel Sir Arnold Wilson, K.C.I.E., C.M.G., D.S.O.; Sir Joseph E. Petavel, K.B.E., Director of the National Physical Laboratory; Sir Henry Fowler, K.B.E.; Sir Brodie H. Henderson, K.C.M.G., C.B., President of the Institution of Civil Engineers; Mr. Daniel Adamson, President of the Institution of Mechanical Engineers; Mr. E. J. Fox, President of the National Federation of Iron and Steel Manufacturers; Sir William Larke, K.B.E., Director of the National Federation of Iron and Steel Manufacturers; Lieut.-Col. K. Edgecumbe, President of the Institution of Electrical Engineers; Professor S. J. Truscott, President of the Institution of Mining and Metallurgy; Dr. W. Rosenhain, F.R.S., President of the Institute of Metals; Mr. Maurice S. Gibb, C.B.E., President of the North-East Coast Institution of Engineers and Shipbuilders; Mr. H. T. Tizard, C.B., F.R.S., Secretary of the Department of Scientific and Industrial Research.

The Loyal Toasts were proposed by the President, and were enthusiastically received.

The Right Hon. Sir PHILIP CUNLIFFE-LISTER, K.B.E., M.P. (President of the Board of Trade), who was received with applause on rising to propose the toast of "The Iron and Steel Institute," said: Mr. President, My Lords, Ladies and Gentlemen—my old friend Mr. Talbot has just said to me, "I wonder how many speeches you have addressed to the iron and steel trade." Well, I hope this will not be the last, but I should like to take this opportunity, if it is the last speech I shall address to the iron and steel trade as President of the Board of Trade—in this parliament

(laughter)—to thank you and your industry for all the help you have given me in the years that I have been at the Board of Trade. Very few men can know all of one industry, and no man, unless he is a very foolish one, can know anything like all of all industries; and the only way anyone can get on in my job is by having continually the advice and the support of the best brains that can be got in the different industries with which he has to deal. If I have failed in regard to iron and steel, it has not been for want of the advice and support that those best qualified to give it in the iron and steel trade have given me, and I am genuinely grateful for their help.

I am grateful to you, moreover, for asking me to come here to-night and propose the toast of your Institute, and to propose it on a particularly felicitous occasion, for this is your Diamond Jubilee year, and some of those who helped to found the Institute are still with us. If I may, as a Yorkshireman, a neighbour, and an old friend, mention one name, which certainly does not exclude others, I should like to mention that of Sir Hugh Bell (applause), to whom I am sure every member of the Institute, whether he came in sixty years ago or this year, sends the very heartiest congratulations on his recovery and the most sincere wishes for his complete restoration to health. It is also the jubilee year of the invention of the basic steel process.

Your charter makes it clear that the primary object of your Institute is to provide a means of communication between members on matters of mutual interest in the scientific development of iron and steel. Never was there greater need for that mutual intercourse or a greater opportunity for getting together in that industry than there is to-day. I am going to give you this toast to-night with a very strong feeling of confidence in the future of the British iron and steel trade. I do not base that only, or chiefly, upon such improvement—and it is not small—as has been seen in that industry in recent times. I base it more firmly and more certainly on the tremendous potentialities which I am convinced the steel trade of this country possesses. We have great assets, if we use them aright. We have a great asset in our industrial relations. I doubt if the record of the industrial relations of any industry is as good as that of the steel industry of this country. You have to be a fairly old member of this

industry to recall the experience of any industrial dispute in the steel trade that led to a stoppage of any magnitude. That is a tremendous asset for any industry. Then there is the asset of the traditional quality and reputation of the goods you produce.

Then you have another asset which is older still—the natural resources of this country : our coal, our ore, and our coast-line. We possess ore in this country on a scale that I think few people outside your own industry recognise. That is a fact which is going to become increasingly important in the years to come, when our great competitors are going short in their domestic supplies. The coast-line of this country is also a real asset. Look at the places where other nations have developed their steelworks, and then look at the coast-line of Britain. In this country you will find harbour facilities and coal side by side, often close to the ore, and in every case with the opportunity of bringing your ore to a port. If you had to start this game over again, could you find any country where the natural advantages are as great as they are in this country for this, perhaps the greatest of all trades ? The earliest industrial predominance of Britain was based on our natural resources and our natural facilities. They are still there, and I am sure they are as great assets to-day as ever they were.

You have also the asset of your plant in this country. I know it is the fashion to-day, particularly in London, to say that the British steel industry wants scrapping from top to bottom, and that we ought to scrap our plant and put in new plant. It is extraordinarily easy to criticise an industry that you do not know anything about, and I have heard that superficial criticism from not a few people—outside the steel area. If, however, you go to an instructed critic (I hesitate to speak before you ; I feel rather like Daniel !) you get a different answer. I had the good fortune a few days ago to meet one who is by common consent the greatest expert in the steel world, a man whose view I would take sooner than anyone else's ; and in the view of such a critic from the steel furnace onwards we have got plant which is in many cases as good as any that can be found anywhere in the world.

When you come to blast-furnaces and coke-ovens, however, I think you yourselves will admit that in many cases your practice falls short of what is best and most economical. Even if you

make a generous allowance for what are called the particular requirements and the particular conditions of different localities I think that is the case, but I know that plans are already in hand for improvement. In this country we have the ore and we have the port facilities, and in the development of pig iron you will be helping not only yourselves but a great many other people as well. I venture to express the hope that the Government may have been of some assistance to you here, and that the reduction in railway freights which it has brought about may have been of material encouragement to many of your firms.

I do not think anyone will deny that to use the assets we possess to the best advantage we do want organisation in the steel industry of this country to go a little further. I know something is being done; I know that some amalgamations have taken place, and that others are contemplated and, I hope I may say, actually in sight. I understand you have already made arrangements for the almost complete co-ordination of your export business, and I congratulate you if that be the fact. I have before now had the experience of two great firms in the same market being after the same contract, and where we have had a minister on the spot who has been only too anxious to support the British interest but who has been unable to give the least help because of the competition of those two firms, neither of which in the end got the contract. If you can co-ordinate your export sales I am perfectly certain you will reap a great advantage, and I congratulate you and look forward to our commercial diplomatic service and our trade commissioners being able to give you far greater assistance than they have been able to render in the past.

But that co-ordination is surely no less important in the home market and in the whole field of production. In all business it is axiomatic that it is worth co-operating in order to eliminate wasteful competition. You know much better than I do how to get the best out of your industry. You want the best plant to be running full time, but you know how seldom the best plant of this country has been running full time. Some of you had to wait until there was a seven-months' strike and all the arrears had piled up in order to see your plant running to the full limit. But not only has the best plant to run full time, but it has to run full time without unnecessary changes; you do not want to have to

be changing over again and again. Rolling-mills which do not need development do want effective use. If they can be kept not only full of orders, but this mill and that mill full of orders of the same kind, the whole cost of production will be affected ; but for this organisation is required. Again, is it not necessary to combine with local arrangements for the establishment of batteries of coke-ovens, with the most efficient plant in the right place for production, for use and for distribution of gas ? I hope that here some help may come from the Committee which I appointed under Sir Alexander Walker.

I may be an optimist when I say that regional amalgamations or arrangements are in sight, but if they are, other arrangements, whether in this country or outside, become much easier. There is no buyer of steel in this country or outside it who need be anxious about the amalgamation or rationalisation of the British steel industry. Its purpose is not to put up prices but to bring down costs of production, and it is only by bringing down costs of production and getting more production that we shall be able to use all our plant, and use it to the best advantage.

Taking the long view, the greater employment of our workmen can come only if our industries are developed as fully as they can be. Your record of your relations with your men, the part your men play, and the understanding your men have of your industry—all these are great assets, and go to show that your men will consider these movements wisely, and that you will consider sympathetically their position. No one can doubt that an industry which is reorganised can command financial support which it cannot command without that reorganisation. When seeking for fiscal or financial support, an industry which has set its house in order has by far the strongest claim.

It is with much pleasure that I give you the toast of your Institute, coupling with it the name of your President, Professor Henry Louis.

The toast was received enthusiastically.

The PRESIDENT of the Institute (Professor Henry Louis, M.A., D.Sc.), who was accorded a very cordial reception, said in reply : My Lords, Ladies and Gentlemen—I rise with very much pleasure

to acknowledge the toast that Sir Philip Cunliffe-Lister has so graciously proposed and you have so warmly accepted. Unfortunately for me, I am not able to follow Sir Philip in the whole of his speech. He, in his position, had the power to couple the iron and steel industry with the Institute. Speaking as your representative and occupying the honourable position to which you have been good enough to elect me, I must confine my remarks to the Iron and Steel Institute, tempting though it is to say a few words on the subjects Sir Philip Cunliffe-Lister has brought before us.

As he has told you, this is our Diamond Jubilee. The Institute is now sixty years old, and, looking back on the progress of the industry during that period, the Institute may fairly be proud of its record. Every important improvement that I can think of in iron and steel making which has taken place during those sixty years has been due to some member of the Institute, and most of them have been wholly originated by our members. (Applause.) That is surely a reflection of which we may well be proud. We must also bear in mind that the way in which our Institute has inspired and assisted research has helped to originate not a few of these improvements in the industry.

Our Institute is entirely British in origin and entirely British in its constitution, but in spite of, or rather I think on account of, that fact it is, I think, the most thoroughly cosmopolitan of all our societies. Our Institute considers no distinction of class or race or nationality; we consider only one distinction—that of doing useful work for the iron and steel industry. That has always been the policy of this Institute, and I am confident it will continue to be its policy in the future. We include people engaged in the manufacture of iron and steel from every part of the world. Go where you will, wherever iron and steel are made you will find a member of this Institute doing his share of the work, helping as one single unit to advance the whole industry, not only in this country but throughout the world.

There is, perhaps, only one regret that I have to voice. While our Institute includes practically every iron and steel maker worth considering, the users of steel are not so well represented in it. I am afraid some of the users do not yet realise how valuable the work of the Institute could be to them. It can be of the greatest value, because the Institute is advancing the scientific

side of the industry by every means in its power. I am afraid the users of steel do not yet thoroughly realise that the days of empiricism are past, and that the old rule-of-thumb methods are no longer to-day as useful as they were at one time. I do not want to have it thought for one moment that I am deprecating the wonderful skill of the trained hand and eye of our workmen. It is a matter for admiration how marvellously their trained eyes do gauge the exact temperatures and requirements for successful manufacture. But nowadays we require more precise and more scientific methods.

For one thing, the intensive working and mass production which are necessities in modern times do not give the time required for the leisurely attainment of correct conditions, which have now to be determined instantly by scientific methods to allow scientific production to go on. Another reason is that modern alloy steel allows, I think, less margin of error than the old-fashioned materials of manufacture. Hence scientific methods are absolutely necessary for anyone who wants to make the best of the material he is handling, and I feel confident that users of iron and steel would find it to their enormous advantage to co-operate more closely with the men who make the materials that they have to use—men who, above all others, understand thoroughly the properties of the metals that they are producing. I make bold to say that the Journal of this Institute and its meetings offer the greatest opportunity possible in the whole world for attaining that knowledge, and I hope that in the future we shall see the users of iron and steel coming forward in greater numbers than they have in the past to co-operate more closely with the manufacturers of these materials, for the mutual advantage of both.

The President of the Board of Trade has told us, as a member of the Government, how useful our Institute has been to him and to all the governing powers. I think I am justified in asking why the Government does not reciprocate. I am speaking now, for the moment, not only on behalf of the Iron and Steel Institute, but on behalf of all the scientific and technical societies of the country, and I make no difference between them, because there is no real difference between pure science and applied science. Science remains pure science only as long as industry has not found the means of applying it, and the pure science of to-day

is the applied science of to-morrow. I am aware that at the moment the gap between pure and applied science is rather large, but that is simply due to the fact that during the last quarter of a century or thereabouts pure science—the knowledge of the constitution of matter, which is, after all, the basis of pure science—has made enormous advances, and applied science has hardly yet caught it up. But that is only a passing phase. The two are, after all, wholly and essentially one, and therefore I think I am justified in speaking on behalf of pure and applied scientific societies as one body. As the President of the Board of Trade has told us, their work has been of the utmost use to the Government. I think they would be justified, however, in quoting to the Government the old lines :

“ It was all very well to dissemble your love,
But why did you kick me downstairs ? ”

(Laughter.) All these societies are having a hard struggle to make ends meet at the present time, for reasons which are too well known to need recapitulating here. They use their income for two purposes only : to disseminate information and to subsidise research. They give no other benefit to their individual members, and because no personal advantage is derived from them they have for years been looked on as public benefactors, and they have on these grounds—and quite rightly, as I maintain—been held to be free from income-tax. In the last year or two, however, the Government authorities have been endeavouring to strain the law and make all these technical societies pay income-tax, which most seriously cripples them and restricts their activities. I venture to suggest that such relatively small sums as can be obtained from them can make no difference to the national budget, though they do make an enormous difference to the budgets of these various societies. It is impossible to suggest any better use that could be made of the national income, wherever derived or obtained, than to apply it to the very work these societies are doing to-day. Surely it is of far greater national importance to develop the national facilities for study and research than to increase the nation's facilities for drinking tea ! If the Government really appreciates the value of scientific work and research as a national asset, let it restrain the activities of the Treasury and

leave the small income of these societies to be utilised, in the future as in the past, for the national benefit.

This Institute is no exception. All it asks is to be given the fullest possible freedom to use its activities in the widest possible way for advancing the great industry which it represents. The gain to the country by the activity of its members in that way will be no less marked in time of peace than it was when members of this Institute were called on, in the dire distress of the country in time of war, to meet the abnormal conditions which then arose. The members of the Institute then rose to the occasion and showed what they could do, and they are equally capable of doing that same work in time of peace. But give us a chance to do it, and leave us alone to do it.

Gentlemen, I think I have said enough to show the important work our Institute is doing. We are endeavouring to co-ordinate the scientific work that is required for a thorough knowledge of iron and steel—a knowledge which is more important to-day, and growing more important day by day, than it has ever been. The members of this Institute are, above all, those who are straining every nerve to produce in the best possible manner that iron and steel which you must look on no longer solely as the implement of warfare but as the handmaid of modern civilisation as we know it to-day, and without which modern civilisation would be unthinkable.

Sir Philip Cunliffe-Lister, I thank you for the way in which you have proposed this toast, and you, gentlemen, for the way in which you have received it. (Applause.)

Sir HENRY FOWLER, K.B.E., who proposed the toast of "The Iron and Steel Industries," said: I feel that perhaps I am, in common with many others, fully qualified to propose this toast, in that I belong to one of the largest industries and largest users of iron and steel—the transport industry of this country, the railways.

I would like you to appreciate what the railways mean at the present time to your industry. As far as figures are concerned, I can speak only for the line with which I myself am associated; but even to-day we purchase considerably over a quarter of a million tons of iron and steel in its semi-finished state (I include

rails), and in addition to that we buy in manufactured articles a very considerable amount of steel.

I feel, moreover, that I am qualified to speak on this toast in that during the war I had the honour of being Director of Production at the Ministry of Munitions. I appreciated then more fully than ever before, and perhaps more fully than many people do, the work done by the iron and steel industry in the great task we had at that time. The President of the Board of Trade and you, Mr. President, have referred to it ; but those of us who were "up against it" did appreciate how, in spite of all the difficulties—and they were many—long before the end of the war we were able to get the whole of the steel we required for our projectiles. I remember realising that, however much we might fail in other directions, we were not going to fail because of insufficient supplies of the steel we required. That, I think, is one of the greatest feats this country has ever performed in the production of munitions, and the basis of our effort was that we were able to get all we wanted in the way of steel supplies.

You will appreciate that it is difficult to hold closely to the subject of a toast, and so I would like to say a word or two with regard to what I feel the industry owes to the Institute. When one looks back at the work that has been done for getting steel into the good condition it is in and (I say it almost with bated breath) at the price it is at, one does appreciate how much the industry is indebted to this Institute.

There are economic reasons which prevent us from progressing as much as we should like to, and that is a point which, unfortunately, we have to consider ; but we cannot go round a steelworks anywhere in the country without appreciating what great strides are being made in our organisation, just as in this Institute we can see what strides are being made. I feel, therefore, it is a great honour that I should be allowed to propose this toast of "The Iron and Steel Industries," and to associate with it the name of my old friend Sir William Larke.

The toast was then honoured.

Sir WILLIAM LARKE, K.B.E., who responded, said : I am really a very bold man to reply to my friend Sir Henry Fowler,

because there is a scriptural injunction which says, "Deliver thyself as a bird from the hand of a fowler." (Laughter.)

When the President of the Board of Trade was speaking, I thought of the many discussions which, as the mouthpiece of the industry, I have had with the Government and its representatives. Let me say at once that I have always met with the most sympathetic and kindly hearing from the President of the Board of Trade individually, but I am reminded of the time when I was myself an amateur Government official. (In parenthesis, let me say that Sir Henry Fowler, when he was Director of Production, turned me down, and, as a reward for his perspicuity, when I had an opportunity later of nominating members of a commission of which I was chairman, he was the first man I thought of.) At a time when we were very harassed, and swamped with papers, we were very glad to find some among them that were not our responsibility. On one occasion an official found such a paper and sent it to a colleague marked "Yours, I think," only to find it back in an hour or so marked "Polite, but inaccurate." (Laughter.) We have sometimes felt that that is the relation which exists between ourselves and the Government; we have been saying "Yours, I think," and they "Polite, but inaccurate," so far as our troubles are concerned. Really, it should have been "Ours, I think." I am glad to find, from the recent Local Government Bill and from many other things which have happened during the past year, that the Government have underlined the "Ours, I think." The derating provisions of the Local Government Act will be a very important contribution towards a national industrial policy by which alone we can secure an industrial revival in this country. The conditions which obtain are quite beyond the powers of the industry to meet with unaided.

It is sometimes convenient for Ministers to say that it is very undesirable that Government should interfere in industry. With that view industry would heartily agree, if Governments had never interfered with industry. It is because they have interfered in the past that they must adjust the consequences of that interference in the present in order that we may secure a revival in the future. The distribution of the burdens of taxation in particular and the burdens of the war can be adjusted only by the Government. The present Government have made a remarkable advance

towards a commencement—I say advisedly and emphatically a commencement—of an industrial policy which I hope, if the fates permit, they will endeavour to develop into a real industrial policy later in this year.

I would like to point out to the Government, which is represented here to-night by Sir Philip Cunliffe-Lister, that it is fatal to tax costs if you want to cure unemployment; you must tax profits. The Government have removed one part of the burden from our costs by the derating scheme, but there is another part, the cost of our social services. Do they realise that we have to pay for the privilege of creating employment an amount which represents 2s. 6d. per week per man and 4s. 6d. per ton of finished steel? It is well worthy of consideration whether that burden cannot be more satisfactorily adjusted, thus giving industry a still greater stimulus.

In our post-war difficulties I have often felt, and I expect the Government and all of you have felt, that we have been too prone to regard masterly inactivity as a policy. It is never a policy; it is always a disease. It is a disease, whether in Government, people, or industry. But I am sure that what I have said will show you the symptoms are subsiding and are in the way of being cured as regards the Government. But what about ourselves? I think it is in process of being rapidly cured, even if we ever had it. I am told that as an industry we are too modest. We have not let the public know what we are doing. I would like to mention one thing that particularly applies to this Institute in which close co-operation has been established—and I gratefully acknowledge it—between the industry and the Government. I hope it will result in very close co-operation between this Institute, as representing the scientific side, and the National Federation of Iron and Steel Manufacturers, as representing what I hope I may call the applied scientific side. We have recently laid the foundation of an Iron and Steel Industrial Research Council which will be composed of members of the Iron and Steel Institute, the National Federation of Iron and Steel Manufacturers, and other research associations of cognate industries connected with iron and steel, and that body will be charged with the responsibility of investigating and developing efficiency in productive processes, plant, and methods. It will

not deal with the fundamental and scientific researches which are already so adequately dealt with by other authorities and through other agencies. I want to acknowledge on your behalf and on behalf of the industry our gratitude to the Government who, through the Department of Scientific and Industrial Research, have agreed to support that work on the basis of a contribution of £ for £ above a datum line of the first £2000 for five years, up to a maximum subscription in any one year of £10,000 by the Department, provided we on our part provide only £12,000 in any one year. That is a very great and important departure. It is one, I think, that warrants my saying that if ever masterly inactivity did infect us it has long ceased to have any meaning in relation to our efforts to redeem our industry from the depression from which it has suffered for so long. I am sure that this Institute will co-operate through its Council and its members to make that great venture an important national feature and the finest research organisation not only in this country but in the world.

There are some pessimistic people, and some who would have it so, who have perhaps thought of our industry as being moribund. When I think of that I am reminded of the man whose obituary notice appeared in the paper. When he complained the editor replied, "What we have said we have said. The best thing we can do is to put you in the births column to-morrow morning." (Laughter.) That is what those people will have to do with the British iron and steel industry. For eight years we have been passing through a difficult time. There is a Latin tag which says, "In poverty, courage is as good as prosperity." I think you will agree that our courage has been well tested. All we need ask is that the conditions within which we can develop our industry shall be at least equal to those enjoyed by our competitors. Given a fair field and no favour, this industry can be and will be second to none.

Sir WILLIAM H. ELLIS, G.B.E. (Past-President), who proposed the toast of "The Guests," said: Mr. President and fellow-members—this is the first time the words "fellow-members" have been employed to-night, but I use them advisedly because, although like any English gentleman I am proud to welcome

ladies to a gathering of this sort, I want to assure them that we accept them with pleasure on account of the academic distinctions they bring with them as members. We are not going to treat them with any more courtesy than I hope we are prepared to extend to each other. They are our fellow-members, and therefore I do not mention them specifically by saying "ladies" in my opening words.

I notice the President of the Board of Trade has, for reasons of his own, departed before I made my speech. Whether his remarks were in the nature of a swan song or not we do not know. (Laughter.) Personally, I hope they were not. We must not mention politics in such a gathering as this, but I think I may say, on behalf of myself and many others, that although he alluded very definitely to the courtesy which had been extended to him by members of this Institute, those of us who have appeared before him to plead various causes have always received from him at least the same measure of courtesy.

My speech to-night is going to be short, but when one proposes the toast of "The Guests" at a gathering of this sort, it is bound to be somewhat invidious. I should like to say that I am prepared to accept the guests as being all equally eminent, and although I am bound to mention certain names that must not be regarded as in any way invidious.

I am sure we all welcome Sir Charles Parsons at our gathering to-night, not only because of the honour which has been bestowed on him to-day, but because we are delighted, knowing his advancing years, to realise that he is as keen and alert in his scientific work as he was a quarter of a century ago. I say a quarter of a century ago, but I believe it is forty-nine years since he and I were in Leeds together, long before he worked out his turbine experiments, so it is really half a century of active scientific research work that he can look back on.

We have many visitors here from different countries, and I offer them a warm welcome on behalf of us all. I am bound to mention two countries in particular. First of all, I hope that our visitor from America will remind his colleagues there that the undistinguished Englishman whom they honoured to the extent of 1654 people welcoming him at the annual dinner last year has not forgotten it, and will never forget the kind hospitality of the

members and the opportunities for viewing their works which were afforded to him. I must also say a word with reference to the presence of Señor Barreiro, who with his colleagues did so much to bring about one of the most successful foreign visits that this Institute has ever made. I hope he will convey to his colleagues in Bilbao our very warm feelings of gratitude for all the trouble they took to welcome this Institute there.

I have to be very careful about my last reference, because it is to the gentleman who is sitting on my left. He now occupies the distinguished position of President of the Institution of Civil Engineers, being one of my successors in office. I have to sit for another six months under his chairmanship, and therefore anything I say about him must be very carefully worded. But I should like to say in his presence that he is doing all that a man can do to maintain the high traditions of that very important technical institution.

Mr. President and fellow-members, I propose the toast of all our guests to-night, coupled with the name of my friend, Mr. Maurice Gibb.

The toast was cordially received.

Mr. MAURICE GIBB, C.B.E. (President of the North-East Coast Institution of Engineers and Shipbuilders), who was received with applause on rising to respond, said: I have very great pleasure, on behalf of your guests, in responding to the toast so ably proposed by my friend Sir William Ellis. I do so, however, with the profound conviction that the one chosen to perform this honourable duty has the least power of expression of all your guests, but, notwithstanding how inadequate my words may be, I feel I am voicing the sentiments of all your guests when I say how heartily we appreciate and thank you for your kind hospitality, and how proud we are to be your guests to-night. There is an old saying that a man is known by the friends he makes, and an Institution might be said to be known by the guests it entertains. If that be so, we guests have to shoulder some responsibility to-night in living up to the high reputation of your great Institute.

Sir Philip Cunliffe-Lister has referred to the basic steel process.

Among the guests who are linked with that early outstanding invention in the steel industry, the basic steel process, which was started at Middlesbrough exactly sixty years ago, are Mr. Thomas and his brother, who are nephews of the late Mr. S. G. Thomas, the inventor of the basic slag process.

I have to speak for, among others, the Presidents and Past-Presidents of other great Institutions who are here to-night. They have been told on many occasions, in what the editor of that great paper, *Engineering*, has described as "terms of harmless adulation," that but for the activities of the members of their own particular Institution the whole fabric of civilisation would drop to pieces. No doubt they, and perhaps we, are inclined to believe it. But, no matter how essential the work of other Institutions may be in keeping the wheels of industry turning, it is impossible to conceive how our industries could carry on without the basic metal from which, Mr. President, your Institute derives its name, and to which your members have devoted so much profound study.

History is marked by the Stone Age, the Bronze Age, and the Iron Age. Our own time is marked by the Steel Age, and, if we may judge by the activity of your members, you are fast approaching what may be known in the next decade as the Rustless Steel Age. If I were allowed to whisper, I might whisper that we shipbuilders are in no great hurry for rustless steel plates. The present plates seem to last quite long enough, though no doubt our friends the shipowners may have other views. (Laughter.)

The increase in the practical applications of science, and the extensive research work which has been done by your members in connection with the great steel industry of this country, will, I am sure, do more than anything else to improve its efficiency and thus carry it through the difficult time through which it is passing, provided that the burden of taxation from which the steel industry, like others, is suffering is removed. I do not wish on this occasion to enter into any controversy with regard to safeguarding, or anything of that kind.

We on the North-East Coast watch the proceedings of your Institute with more than ordinary interest, not only because your President and his immediate predecessor hail from that area,

but because our industries, and particularly our shipyards, are dependent on an efficient steel industry. It is therefore of particular interest to us to know that your members are going to pay a visit to Newcastle in September, and I am sure you will receive a very hearty welcome.

I thank you on behalf of your guests for the hearty way in which you have honoured this toast.

The proceedings then terminated.

SECTION II.

*NOTES ON THE
PROGRESS OF THE HOME AND FOREIGN
IRON AND STEEL INDUSTRIES.*

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The Editor has been assisted in the preparation of these Notes by
R. ELSDON, Librarian of the Institute.

MINERAL RESOURCES.

BRITISH EMPIRE.

Southern Extension of the Warwickshire Coalfields. F. W. Shotton. (Transactions of the Institution of Mining Engineers, 1928, Vol. 76, pp. 136-148). The paper embodies the results, in so far as they bear upon the future exploitation of coal in Warwickshire, of a detailed geological investigation which the author made during 1927 and 1928 upon an area lying between Coventry and Warwick.

Notes on East Coulee Coal Area, Alberta. G. L. Kidd. (Canadian Mining and Metallurgical Bulletin, 1929, Mar., pp. 490-494). A short paper in which the author shows the relations of the East Coulee coal area to the near-by Willow Creek, Wayne, Rosedale, and Drumheller areas. A table is included giving the analyses of several coals from the Drumheller field.

The Peat Industry at Alfred, Ontario. (Engineer, 1928, Vol. 146, Nov. 23, pp. 566-568). The Provinces of Ontario and Quebec are almost entirely dependent on imported coal. In these two Provinces there are, however, about 11,000 square miles of peat bogs, of which a considerable amount is suitable for the preparation of peat fuel. Twenty-two bogs, containing an estimated reserve of 87,000,000 tons, are close to large centres, and it is from these that a yearly production of 500,000 tons of peat, to be marketed as an industrial fuel and as an auxiliary to coal for domestic purposes, is predicted. The article gives a brief account of the history of the development of the Canadian peat industry, which is largely a story of failure. The plant now being operated at Alfred by the Federal Department of Mines is described.

Oil and Gas in Western Canada. G. S. Hume. (Canada, Department of Mines, Geological Survey, Economic Geology Series, No. 5, 1928). The report contains chapters on the origin and accumulation of oil and gas, carbon ratios of coal as an index to the occurrence of oil and gas in Western Canada, geophysical methods for locating oil, physiography and stratigraphical geology of the Great Plains, and descriptions of the oil and gas fields. An appendix gives a list of wells drilled in Manitoba, Saskatchewan, Alberta, North-West Territories, and British Columbia.

Manganese Deposits at Postmasburg, South Africa. H. M. Pezzani. (Iron and Coal Trades Review, 1929, Vol. 118, Apr. 12, p. 540). According to the author these deposits have been proved over a length of 40 miles. Sinkings on the Southern farms indicate a thickness of seam up to 54 ft., and on two farms alone, covering an area of approximately 500 acres, it is estimated that 75 million tons of ore are available for mining. Approximately 60 per cent. of the ore on the Southern farms carries between 50 and 59 per cent. of manganese.

The Chrome Industry of Southern Rhodesia. (South African Mining and Engineering Journal, 1928, Vol. 39, July 7, pp. 539-542).

Mineral Resources of the Gold Coast. (Bulletin of the Imperial Institute, 1928, Vol. 26, No. 4, pp. 481-482). Some notes are given on deposits of bauxite, manganese, and limestone found by the Geological Survey during the half-year ended June 30, 1928. In the Yenahin district, some 40 miles west of Kumasi, the deposits of bauxite found by the Geological Survey in 1923 were further examined. The deposit has been proved to be from 20 to 50 ft. thick and to contain very large quantities of good bauxite. Associated with the Yenahin bauxite in one locality are large masses of manganese ore, some of which is of high grade.

Mineral Resources of Sierra Leone. (Bulletin of the Imperial Institute, 1928, Vol. 26, No. 4, pp. 483-485). Ilmenite and titaniferous magnetite are widely distributed in the Peninsular of Sierra Leone. Individual deposits vary greatly in composition, from nearly pure ilmenite to magnetite containing only a small quantity of titanium. The following analyses are of samples from lodes in the norite near Hastings and Mount Aureol, Freetown.

	Hastings.		Mt. Aureol.	
	%		%	
Fe ₂ O ₃	25.06	}	76.92	76.36
FeO	28.02			
TiO ₂	42.34		15.70	7.44
V ₂ O ₅	0.38		0.69	...
Cr ₂ O ₃	Nil		4.36	3.16

Geology of the Bowen River Coalfield. J. H. Reid. (Geological Survey of Queensland, 1929, Publication No. 276).

The Geology of the Umaria Coalfield, Rewah State, Central India. E. R. Gee. (Records of the Geological Survey of India, 1928, Vol. 60, pp. 399-410).

The Occurrence of Low-Phosphorus Coking Coal in the Giridih Coalfield. C. S. Fox. (Records of the Geological Survey of India, 1926, Vol. 59, pp. 371-404).

Sampling Operations in the Pench Valley Coalfield. G. V. Hobson. (Records of the Geological Survey of India, 1926, Vol. 59, pp. 165-190).

EUROPE.

Iron Ores of North-Western France. E. C. Eckel. (Engineering and Mining Journal, 1929, Vol. 127, Mar. 9, pp. 392-393). The ore deposits of Normandy and Anjou are described.

Industrial Spain Enriched with Mineral Treasures. V. Delport. (Iron Trade Review, 1928, Vol. 83, Oct. 4, pp. 829-832). Information obtained from official sources, relating to the iron ore and fuel resources of Spain, is given.

The Minerals and Mining Industries of Czechoslovakia. J. G. F. Druce. (Chemistry and Industry, 1929, Vol. 48, Feb. 22, pp. 189-190). Both hard coal and lignite are mined in considerable quantities (about 14 and 23 million metric tons per annum respectively). The largest coal deposits are in Kladno, Rakovnik, and Pilsen districts of Bohemia and around Ostrava in Silesia. This coalfield adjoins those of Poland and Germany, and consequently meets with heavy competition. The Rakovnik mines are the oldest, having been worked in the seventeenth century. The largest deposits of lignite are the three basins in N.W. Bohemia, below the Ore Mountains—namely, Most-Chomutov-Teplice (Brüx-Komotau-Teplitz), Falknov-Loket (Falkenau-Elbogen), and Cheb (Eger). Some of the lignite is obtained just under the surface and without the sinking of shafts. The calorific value averages about 4000 cal., but varies between 3000 and 7000. Much is exported from these districts to Germany, chiefly Bavaria. The output of iron ore (2,000,000 metric tons annually) is about equally divided between Bohemia (chiefly from Krušna Hora) and Slovakia (Dobšina, Špiš, &c.). The chief foundries are at Pilsen, where the Skoda works are situated, Vitkovice and Kralův Dvůr (Königshof). Iron pyrites is found abundantly, but it is not mined for the metal.

The Iron Ore Deposits of the Lölling-Hüttenberg-Friesach Range in Carinthia. H. Haberfelner. (Berg- und Hüttenmännisches Jahrbuch, 1928, Vol. 76, Oct. 1, pp. 87-114; Dec. 15, pp. 117-126).

The Coals of the Bulgarian Central Balkans. I. Trifonow and E. Raschewa-Trifonowa. (Glückauf, 1928, Vol. 64, Nov. 3, pp. 1490-1491). The composition, calorific value, and types of coals occurring in fourteen mines in the district are recorded and discussed.

AMERICA.

Analyses of West Virginia Coals. (United States Bureau of Mines, 1928, Technical Paper No. 405). This paper forms one of a series containing analyses of the coals of the different States of the United States. A brief description is included of the geological structure of the coal-basins in West Virginia and of typical mining conditions.

The Pumpkin Buttes Coalfield, Wyoming. C. H. Wegemann, R. W. Howell, and C. E. Dobbin. (United States Geological Survey, 1928, Bulletin 806A). The geography, geology, and coal-bearing areas are described. The coalfield embraces about 1800 sq. miles in the central part of the Powder River Basin in North-Eastern Wyoming.

Mineral Industry of Alaska in 1927 and Administrative Report. P. S. Smith. (United States Geological Survey, 1929, Bulletin 810A).

ASIA.

Investigations of Japanese Coals. H. Winter. (Glückauf, 1929, Vol. 65, Apr. 13, pp. 493-498). The output of coal in Japan amounted to about 28 million tons in 1923. The largest deposits occur in the islands of Hokkaido and Kyushu. The coals belong to the tertiary formation; all types of coals from lignitic brown-coal to anthracite occur. The coking industry is carried out along modern lines. The analyses of five coals from various places are recorded, and the occurrence of ash is discussed; the volatile matter contents lay between 39 and 47 per cent. of the cleaned coal. The distribution of the ash was investigated by means of X-rays and by very careful incineration of coal laminæ. The constitution of the coals was also investigated.

Geographical Distribution of Certain Minerals in Japan. S. Imori and T. Yoshimura. (Supplement to Scientific Papers of the Institute of Physical and Chemical Research, Tokyo, 1929, Vol. 10, pp. 5-46). The localities producing the chief minerals in Japan are listed.

Geology of the Wu Hu Tsui Coalfield, Fuhsien, Fengtien. C. C. Wang. (Bulletin of the Geological Survey of China, 1928, No. 11, Oct., pp. 37-49). The topographical features, stratigraphy, structural geology, and coal resources of this coalfield are described.

Oil, Coal, and Iron Enterprises in South Manchuria. W. F. Collins. (Engineer, 1929, Vol. 147, May 3, p. 486).

ORES—MINING AND TREATMENT.

A New Micromagnetometer. F. Rieber. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 119). The development of magnetic surveying would seem to have reached an instrumental limit, beyond which little progress may be expected unless some new principle of instrument construction can be introduced. The instrument described is believed to embody such a principle. The experimental model first constructed showed an apparent accuracy of over 30 times that of typical field balances. Due to the lightness and strength of the wire which constitutes the one moving part, and to other features of construction, greater dependability as well as greater accuracy are obtained.

Certain Aspects of Magnetic Surveying. L. B. Slichter. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 120). In classifying rocks magnetically, the inert, highly magnetic, and intermediate types are briefly discussed, and the peculiar importance of a few of the ferric minerals, and especially magnetite, is explained. Experimental evidence shows that the susceptibility of magnetite changes greatly as the field strength is changed, and that it also depends very much on the form in which the magnetite occurs. The hitherto accepted values appear far too low. For fields as weak as the earth's, a value of about 0.3 is obtained for disseminated magnetite, while for the solid material a value of 1.5 to 3.0 or higher appears correct.

Three instances are given of the fact that field observations of intensity are often much in excess of those which can well be accounted for by accepted values of the susceptibility. In each case the higher values here advocated appear adequate to account for the observed results—in two cases it is shown that there is a satisfactory quantitative agreement between observed magnetic data and the form and size of the known ore body which caused the magnetic response.

Geophysical Prospecting : Some Electrical Methods. A. S. Eve and D. A. Keys. (United States Bureau of Mines, 1928, Technical Paper 434). The experiments show that a certain amount of valuable information as to the existence and distribution of an ore body can be obtained with equipment that is procurable with comparative ease by the mining engineer. However, the means of detecting the ore

are not equally adaptable under all conditions, and the principles underlying geophysical prospecting methods must be judiciously applied with a great amount of study and caution, as well as sound theoretical knowledge and extensive field experience. Even with these as background the methods in their present stage of development are not altogether reliable.

Manganese Ore Mining by Underground Methods in the Central Provinces, India. B. V. Mellon. (Transactions of the Mining and Geological Institute of India: Iron and Coal Trades Review, 1929, Vol. 118, Feb. 8, p. 207). The methods of mining employed at the Balaghat manganese ore deposit owned by the Central Provinces Manganese Ore Co., Ltd., are described.

Calculations in Ore Dressing. W. Luyken and E. Bierbrauer. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 214).

Modern Apparatus for the Preparation of Iron Ores. H. Bartsch. (Stahl und Eisen, 1929, Vol. 49, Mar. 14, pp. 353-355). In the washing of aluminous and siliceous ores in ordinary revolving washing drums trouble is experienced through the balling up of the clayey substances into lumps to which iron ore particles adhere, so that considerable losses result. Moreover, the lumps for the most part do not disintegrate and have to be removed by manual work from the drum. By fixing rings of triangular knives inside the drum at short intervals along its length this difficulty is overcome. The stream of water enters the drum counter to the direction in which the ore travels, and the cutting action of the knives, together with the friction of the revolving drum, completely disintegrates the sticky mass. Any particles of ore carried off with the mud are screened out on mud screens at the end of the drum and fed back into it. A second drum fitted with buckets or scoops works in series with the first, and here a final washing is effected, giving a good clean concentrated ore. The clay ores of Hesse containing iron 25 to 30, silica 30, and alumina 18 to 25 per cent. are treated in this way and yield a concentrate with iron 47, silica 9 per cent. and free from alumina. The market value of the ore is increased by 8s. 9d. per ton. At most ore washeries it is essential to recover the water, and to avoid the use of settling tanks covering a large space of ground which need continual cleaning, a mud-concentrating table is used. The clear water flows off the top, while the sludge is collected in a sump underneath and is continuously removed by a sludge pump. No sieves, filters, compressors, spitzkasten, or long lines of suction pipe are necessary. All these appliances, as well as single-stage screens for ores containing lumps of stone or pebbles, are described and illustrated.

Investigations concerning the Technical and Economic Efficiency of the Spathic Ore Dressing Plant at the San Fernando Iron Mines. W. Luyken and E. Bierbrauer. (*Archiv für das Eisenhüttenwesen*, 1928, Vol. 2, Dec., pp. 361-362). The article forms a short appendix to the previous report by the same authors previously published in *Archiv für das Eisenhüttenwesen*, 1928, Vol. 1, Jan., pp. 467-480 (*see* Journ. I. and S.I., 1928, No. 1. p. 719). Some further explanations of the method of calculating the costs of the cleaning and roasting process as compared with those of hand-picking and roasting by other kilns are given.

The Magnetic Roasting of Iron Ores. W. Luyken and E. Bierbrauer. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Mar., pp. 531-543). The term "magnetic roasting" implies a method by which a feebly magnetic iron mineral contained in iron ores is transmuted into the ferro-magnetic form of iron. The treatment is applicable to hematite, limonite, and to mixtures of such ores with magnetite. Spathic ores treated with a view to subsequent magnetic separation may also be regarded as having been subjected to magnetic roasting. The authors describe experiments made at the Kaiser-Wilhelm-Institut für Eisenforschung in treating the brown and red hematites from the Salzgitter range and the Dill basin with a view to rendering them ferro-magnetic. Samples of these ores, 2 to 3 kg. in weight, were roasted at 500° to 700° C. in a rotary electrically heated furnace. Working under exclusively reducing conditions the ferric oxide can be entirely converted into a ferro-magnetic oxide. Ordinary town gas was used as the reducing agent. After roasting for 10 to 20 min. the ores readily lent themselves to magnetic concentration.

Grading of Minette Ore and the Influence thereof on the Smelting Process. E. Bertram. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Feb., pp. 461-469). The minette ores of Lorraine and Luxemburg differ among themselves in refractoriness and capacity for disintegration. Certain types of minette ores disintegrate at once on heating to between 180° and 250° C. Careful examination of the constitution of these ores leads to the conclusion that the disintegration is due to the expansion of the moisture of the green iron-silicate gels and of the brown iron-hydroxide gels which very commonly occur in the minette ores high in lime. The siliceous minette ores, on the other hand, do not disintegrate, but the lumps retain their form practically unaltered till they sink to the tuyere level in the blast-furnace. The disintegrating type of ore can neither be usefully dried nor sized before charging. Trials in blast-furnaces and smaller experimental furnaces with the graded refractory ores show that the iron produced is more uniform and is of a better physical and chemical character. By grading the ore to a size not over $2\frac{1}{4}$ in. a saving of 2 to 5 per cent. in coke was made, which was just about enough to cover the cost of interest and

depreciation on the crushing plant. On the other hand, the crushing and grading of the ore led to an increase in the quantity of flue-dust carried over from the furnace, and this could only be remedied by screening out the fines before charging and by agglomerating them in a sinter plant.

Experiences with the Lurgi Sinter Apparatus. M. Blau. (Stahl und Eisen, 1929, Vol. 49, Mar. 21, pp. 388–392). The utilisation of the manganiferous ores obtained from the Geier mine at Waldalgesheim has been previously shown to be dependent on finding a practical method of sintering so as to obtain a lumpy material suitable for the blast-furnace. When dried at 100° C. the ores contain iron 25 to 27, manganese 16 to 17, silica 13 to 15, alumina 8, hydrates 8 to 10 per cent. They are powdery, and after sintering the agglomerate contains about 30 per cent. iron and 17 per cent. manganese. A Lurgi sinter plant fired with producer-gas from brown-coal briquettes was installed. The fuel consumption, however, exceeded what had been estimated, and a Deutz anthracite producer was substituted for the brown-coal gas-producer, by which the efficiency was improved. Nevertheless, owing to the very difficult nature of the ore, the loss in dust and smalls was about 26 per cent. of the theoretical output.

The A.I.B. Sinter Plant at Messrs. Guest, Keen and Nettlefolds, Ltd., Cardiff Works. W. E. Simons. (Paper read before the Iron and Steel Institute, May 1929: this Journal, p. 89).

Recovery of Apatite from Iron Ore Sludge by the Flotation Process. W. Luyken and E. Bierbrauer. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 317–321; Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Dec., pp. 355–359). The article describes the treatment of the waste sludge remaining after concentrating the fine dust, or “slig,” which is magnetically separated from the magnetite lump ore mined at Lekomberg in the Grängesberg district of Central Sweden. The lump ore contains 54 to 57 per cent. iron, and the fines which go for concentration after dry separation from the lump ore contain iron 42 per cent., and 0.6 to 1 per cent. of phosphorus. These fines after wet magnetic concentration contain iron 63 per cent. and phosphorus 0.3 per cent.; the amount of waste sludge resulting from the process is 38 per cent. by weight of the total fines treated, and it contains iron 8 per cent., phosphorus 2 per cent. The phosphorus is mainly in the form of the non-magnetic compound apatite. The recovery of this apatite by the flotation process using sodium palmitate as a froth producer has been tried on a large scale with success, but in view of the high consumption of the reagents the process is only economically possible if the flotation liquor is recovered and circulated afresh. The resulting concentrate is 17.28 per cent. by weight of the original sludge and contains up to

15.7 per cent. phosphorus, the product being of value as an addition in furnaces running on basic pig iron.

Metallisation of the Oxide of Iron in Ilmenite. R. J. Traill and W. R. McClelland. (Paper read before the American Electrochemical Society, May 1929). The metallisation of the iron oxide in ilmenite is accomplished by treating the crushed ore mixed with coal and coke in an oil-fired rotary kiln furnace, with the exclusion of excess air. The iron associated with the bulk of the titanium dioxide is separated from the unconsumed coal, coke, and gangue material by magnetic separation. Over 92 per cent. metallisation of the iron is obtained. Leaching of the metallised product with a suitable solvent extracts the iron, leaving a high-grade titanium dioxide concentrate.

REFRACTORY MATERIALS.

Refractory Materials. W. R. D. Jones. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Feb. 7, pp. 103-104). The chief characteristics of silica and fireclay refractories are dealt with.

Some Properties of Refractories. J. B. Shaw. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Dec., pp. 1612-1613).

Progress in the Refractories Industry. J. S. McDowell. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 88-90, 189; Heat Treating and Forging, 1929, Vol. 15, Feb., pp. 187-189). A summary of the principal developments in the manufacture and use of refractory materials of various kinds.

Developments in the Manufacture, Uses, and Applications of Refractories. M. C. Booze. (Fuels and Furnaces, 1929, Vol. 7, Apr., pp. 567-571).

Latest Processes for the Production of Refractory Materials. W. Obst. (Feuerfest, 1929, Vol. 5, Jan., pp. 4-5). Brief notes of recent patent specifications and some short references to up-to-date literature are given.

The Refractories Used in Metallurgy: Properties, Tests. P. Gilard. (Revue Universelle des Mines, 1928, Vol. 20, Nov. 15, pp. 170-202). The properties, uses, and tests of refractories are discussed in detail.

Silica as a Refractory in Steel Industry. R. B. Sosman. (Paper read before the American Iron and Steel Institute, May 1929). The properties of silica are discussed under the following headings: Silica as raw material; melting point; thermal inversions and expansions; and relations of silica to other oxides.

The Physical Structure of Refractory Materials. T. S. Curtis. (Journal of the American Ceramic Society, 1928, Vol. 11, Dec., pp. 904-916). The relation of physical structure to the performance characteristics is pointed out. It is shown that chemical composition is of value principally as a means of control of raw materials, the value of the end
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product being determined largely by the crystallographic relationship existing between grain and bond.

Appliances for the Testing of Refractory Materials. F. Fromm. (Glückauf, 1929, Vol. 65, Jan. 26, pp. 144-146). The refractories testing plant of the Verein zur Überwachung der Kraftwirtschaft der Ruhrzechen (Society for the supervision of power economy of the Ruhr Collieries) at Essen is described.

Concerning the Testing of Refractory Products. E. L. Dupuy. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : Chaleur et Industrie, 1928, Vol. 9, Nov., pp. 801-802).

Determination of the Specific Gravity of Refractory Materials. E. Kühn. (Feuerfest, 1929, Vol. 5, Jan., p. 5). Very brief details and a photograph of the author's "Volumoscope" are given; the determination is carried out *in vacuo*.

The Thermal Expansion of Fireclay Bricks. A. E. R. Westman. (Illinois University, Engineering Experiment Station, 1928 : Bulletin No. 181).

Determination of the Sensitiveness of Refractory Constructional Materials to Variations of Temperature. W. Miehr, J. Kratzert, and H. Immke. (Tonindustrie-Zeitung, 1928, Vol. 52, Jan. 11, pp. 56-60; Jan. 14, pp. 77-78). The authors discuss present-day methods of determining the sensitiveness of refractories to changes of temperature; a large number of tests showed that the American process indicated only slight differences between the bricks tested, that of the Dampfkessel-Ueberwachungsverein showed larger divergences, while a new method, in which the rapid cooling was brought about by a jet of water and compressed air, made the greatest distinctions. The authors propose a new operating process for silica, Dinas, and highly siliceous fireclay bricks, and describe a special furnace in which the heating and cooling periods may be varied within very wide limits.

The Failure of Refractory Materials at Very High Temperatures. M. W. Travers. (Chemistry and Industry, 1929, Vol. 48, Feb. 1, pp. 106-107).

Mechanical Tests of Refractories at High Temperatures. E. L. Dupuy. (La Céramique, 1928, Vol. 31, pp. 225-230).

A Simple Method for Determining the Cohesion of Refractory Products at Room Temperature. A. Jourdain. (La Céramique, 1928, Vol. 31, pp. 230-238). The author describes a new test for cohesion

at room temperature, and discusses the mathematical physics of phenomena which underlie the test.

The Effect of Substituting High-Silica Sand for Some Grades in Lime-Bonded Silica Bricks. W. Hugill and W. J. Rees. (Transactions of the Ceramic Society, 1929, Vol. 28, Feb., pp. 62-64).

The Effect of Thermal Shock on the Transverse Strength of Fireclay Brick. C. W. Parmelee and A. E. R. Westman. (Journal of the American Ceramic Society, 1928, Vol. 11, Dec., pp. 884-895). An apparatus is described by means of which a firebrick, initially at a temperature of 1100° C., could be subjected to definitely localised thermal stresses by cooling the centre of one face of the brick with an air-blast, the remaining surface of the brick being protected by insulation. By means of this apparatus, the effect of thermal shock on the transverse strength of twenty brands of fireclay brick was determined. The values obtained are compared with the other physical and chemical properties of the brands. The advantages and disadvantages involved in the use of this method as a laboratory test for the determination of resistance to thermal shock are discussed.

After Diaspore—What? A. F. Greaves-Walker. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Nov., pp. 1481-1482). The author points out that the reserves of diaspore, the only known commercial deposits of which occur in East Central Missouri, are small, and, as the demand for such a high-alumina refractory is great, he suggests as substitutes cyanite, bauxite, and Georgia kaolin. He reviews briefly the properties of these refractories.

Dinas Bricks. V. E. Grum-Grjimalo. (Journal of the Russian Metallurgical Society, 1928, No. 3, pp. 55-60). (In Russian.)

Tridymitisation of Dinas Bricks. V. N. Schvecov. (Journal of the Russian Metallurgical Society, 1928, No. 3, pp. 61-71). (In Russian.)

Some Effects of Coal-Ash on Refractories. T. N. McVay and R. K. Hursh. (Journal of the American Ceramic Society, 1928, Vol. 11, Dec., pp. 868-873). The action of coal-ash on the following types of refractories was studied: (1) high diaspore brick; (2) fireclay refractories with very little quartz; (3) fireclay refractories with considerable quartz; (4) refractories containing a mixture of diaspore and fireclay; and (5) andalusite refractories. The tests were carried out in a rotary furnace at temperatures ranging from 1500° to 1600° C. The phases present in the coal-ash refractory slag were identified by means of the petrographic microscope, and consisted of magnetite,

mullite, and glass. The effects of duration of slag action and slagging temperatures were studied.

Effect of Typical Slags on Firebrick, with a Method of Determination Correlated to Service. C. E. Grigsby. (Journal of the American Ceramic Society, 1929, Vol. 12, Apr., pp. 241-263). An account is given of an investigation undertaken to determine the resistance of firebricks to slags encountered in service. Laboratory slag tests were made in a rotary slagging test furnace, which is described together with the method of operation. Bricks which gave the best results in the laboratory were tested in service in malleable iron furnaces, cupolas, and ladles where sodium carbonate was used.

The Crushing Strength of Unfired Fireclay Bodies. W. C. Hancock and J. G. Cowan. (Transactions of the Ceramic Society, 1927-1928, Vol. 27, pp. 243-246).

Results of Comparative Tests on Slag Bricks. W. Schäfer. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Dec., pp. 363-366). Compression tests on bricks of blast-furnace slag show that the form of the test-piece has a very considerable influence on the result. Tests were made on whole bricks, half-bricks, two half-bricks cemented together, and cubes and cylinders cut from bricks. The resistance of different shaped specimens from bricks of the same quality varied from 304 to 127 kg. per sq. cm. The reason for the great divergencies is not cleared up and further investigations are necessary.

Investigations of the Slagging of Refractory Materials. H. Salmang and F. Schick. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Jan., pp. 439-447). The research aims at throwing light on the complex reactions between highly refractory silicates and fused silicates, and the crucible method was adopted for the purposes of studying them. The slag or slag constituent, the action of which it was desired to discover, was fused in crucibles of special design with very thick walls, and after completion of the melt the crucibles were sawn transversely in two just above the bottom, and the parts eroded by the slag were measured planimetrically. The erosion of the sides was not taken account of, and only the erosion of the bottom was measured. The mass from which the crucibles were made consisted of 6 parts fireclay and 4 parts binding clay, the composition of the crucibles being SiO_2 58.26, Al_2O_3 38.62, Fe_2O_3 1.68, TiO_2 1.56, and K_2O 0.81 per cent. The slags were synthetically compounded from oxides, silicates, phosphates, carbonates, borax, and the sulphate MnSO_4 , all obtained in the purest possible form from a firm of chemists. In respect to the strength of their attack on the fireclay the oxides when heated in their pure form are ranged in the following order: PbO , FeO , MnO , CaO , Fe_2O_3 , K_2O , Na_2O , Mn_2O_3 . When completely fused the above order

is changed for some of them, and these are then ranged as follows: CaO , FeO , MnO , Fe_2O_3 , MgO . Silica and alumina act as diluents in respect to slag attack on the basic oxides, as is shown by the behaviour of open-hearth slags and cupola slags. These contain about the same amount of iron oxides, but differ as regards lime and silica. The open-hearth slag attacks basic materials strongly, but the cupola slag hardly at all. Slags high in lime (40 per cent.), to which iron and manganese oxides are added in considerable quantity, become thin fluid, and their attacking effect is thereby very greatly increased, as they penetrate the pores of the firebrick much more easily.

Drying Cracks in Firebricks. C. E. Moore. (Transactions of the Ceramic Society, 1929, Vol. 28, Apr., pp. 193-203). A discussion of some of the causes for the occurrence of drying cracks in firebricks. Drying cracks as found in ordinary manufacture may be roughly divided into two classes. The first consists of those cases in which failure is due solely to the faulty conduct of the drying operation, whereby uneven drying and consequent strain has been produced. The second consists of those cases in which faulty mixing, extruding, moulding, or pressing provides the original cause, although, of course, the drying treatment may also be of great importance in determining the magnitude of the resultant failure.

Stoker-Fired Tunnel Kilns Used in Burning Firebrick. D. B. Hendryx. (Fuels and Furnaces, 1929, Vol. 7, Feb., pp. 225-228). A description is given of two installations in which firebricks are made principally by the press process and burned in stoker-fired tunnel kilns of the Dressler type.

A Tunnel Kiln Refractories Plant. B. E. Whitesell. (Journal of the American Ceramic Society, 1929, Vol. 12, Feb., pp. 96-106). A description is given of the Salina plant of the Kier Firebrick Co., where all the ware is fired in two hand-fired car tunnel kilns.

Employs Tunnel Kilns for Burning Fire and Clay Brick. F. B. Pletcher and W. G. Gude. (Iron Trade Review, 1928, Vol. 83, Dec. 27, pp. 1617-1620, 1622). Illustrated particulars are given of an installation of tunnel-fired kilns at the plant of the Harbison-Walker Refractories Co., Pittsburgh. The kilns are stoker-fired and are each 444 ft. in length.

Refractories in the Gas Industry. E. W. Smith and H. M. Spiers. (Chemistry and Industry, 1928, Vol. 47, Dec. 7, pp. 1278-1284). The chief requirements which must be fulfilled by bricks used in the carbonising industry are as follows: constancy of volume, freedom from spalling tendency, refractoriness under load, chemical stability,

mechanical strength, thermal conductivity, and good shape and texture. These requirements are discussed.

Properties of and Specifications for Silica Bricks for Coke-Ovens. H. Knuth. (Feuerfest, 1929, Vol. 5, Feb., pp. 21-26). The various requirements demanded of silica bricks in practice are reviewed, and properties and tests of which use can be made in order to judge the quality of the bricks are discussed. The specifications of nine firms and the suggestions of Endell and Pfeifer are compared. Proposals for uniform standardisation of silica content, refractoriness, specific gravity, and total porosity are put forward.

Mortar for the Construction of Coke-Ovens. P. B. Robinson. (Feuerfest, 1929, Vol. 5, Feb., pp. 13-15). The most suitable mortar for refractory (clay) bricks appears to be a mixture of clay, grog, and sand in the proportions of 2 : 1 : 1. For coke-ovens where slagging is not to be feared and where attention can be given from time to time, a mixture of clay and grog alone is suitable. For silica bricks in coke-ovens, a mixture of 10 per cent. plastic clay, 30 per cent. grog, and 60 per cent. ganister can be used; this mixture is not suitable for gas-works use. To determine the behaviour of a mortar in practice, the author recommends loading trials and tests for its attack by slag.

Preventing Shattered Shaft Linings. (Iron Age, 1929, Vol. 123, Feb. 14, pp. 480-482). **Modern Refractories Laboratory is Aid to Research.** H. R. Simonds. (Iron Trade Review, 1929, Vol. 84, Apr. 18, pp. 1049-1051). An account is given of the equipment used in the laboratory of the General Refractories Co., Baltimore, to study the effect of carbon monoxide on firebricks used for blast-furnace linings. The results of experiments show that the disintegration of blast-furnace linings is caused by the presence of free iron oxides in the brick.

Destruction of Brick by Carbon Monoxide. E. Diepschlag and K. Feist. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 280-282). An abridged translation of a German article. (See Journ. I. and S.I., 1928, No. II. p. 246.)

Employ Improved Refractory Shapes in Lining Inland Stacks. F. J. Binckes and H. W. Lindhardt. (Iron Trade Review, 1929, Vol. 84, May 9, pp. 1260-1261). Particulars are given of a firebrick of new design which is used in lining the blast-furnaces of the Inland Steel Co., Indiana Harbour.

Refractories for the Cupola. C. E. Bales. (Transactions of the American Foundrymen's Association, 1928, Vol. 36, pp. 683-696). A general description is given of the various processes for the produc-

tion of cupola blocks. Their properties and behaviour in use are also discussed.

Monolithic Linings for Cupolas. G. H. Zirker. (Die Giesserei, 1928, Vol. 15, Nov. 16, pp. 1145-1149). The author discusses the properties required in material to be used to make monolithic linings for cupolas, both from the point of view of the construction of the lining and with regard to the conditions which it will have to resist while the cupola is in operation.

Durability of Rammed and Jolted Converter Bottoms. H. Weiss and P. Röllner. (Stahl und Eisen, 1928, Vol. 48, Dec. 13, pp. 1737-1742). Trials at Völklingen have shown that the average life of a rammed dolomite converter bottom, 28 in. thick and about 65 in. diam., was 38.3 charges. It was decided to adopt the jolting method for making these bottoms and a jolting machine was installed, which is illustrated and described in the article. The jolted bottom takes one-quarter the time to make compared with that required for making a stamped bottom, and the life of a jolted converter bottom is 15 per cent. longer. The jolting takes about 5 min. under a pressure of 8 atm. For burning, the heating up should take 24 hr., the temperature should be maintained at 700° C. for 24 hr., and 48 hr. should be allowed for cooling down.

Magnesite or Dolomite for Basic Bottoms. M. Karnaoukhov. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Apr., pp. 545-547). The author deals with the use of magnesite for making up and repairing the bottoms of basic open-hearth furnaces. In the majority of cases where magnesite is used the result is said to be more profitable than with the use of burned dolomite alone or in mixture with a part of burnt magnesite, notwithstanding that magnesite is the more expensive material, because the clean magnesite bottom works better and requires less repairs than the dolomite bottom.

Durability of the Lining of Direct Arc Furnaces under Various Operating Conditions. E. Kothny. (Feuerfest, 1929, Vol. 5, Jan., pp. 1-3, Apr., pp. 75-80). The author reviews the replies received to a questionnaire circulated by the Verein deutscher Giessereifachleute, and discusses the durability of furnace roofs of various constructions, and under various conditions of operation.

Production of Magnesia and Silica Crucibles in the Induction Furnace. C. N. Schuette. (United States Bureau of Mines, 1928, Reports of Investigations, Serial No. 2896). The author describes the production in the high-frequency furnace of silica crucibles of greater wall thickness than could be readily fabricated from commercial fused silica, and of heavy walled magnesia crucibles of great density and mechanical strength. Drawings are given of the methods used in the preparation of

the crucibles, and the method of procedure used in making the crucibles as well as mixes and materials are given in detail.

Hartmann Spiral Bricks. J. Tornblad and W. B. Mitchell. (Journal of the West of Scotland Iron and Steel Institute, Session 1928-29, Vol. 36, pp. 28-34). The authors discuss the application of Hartmann spiral bricks for hot-blast stoves and give particulars of the saving effected by their use. The spiral bricks in conjunction with their bearer bricks can be placed on top of existing checker brickwork, but in the case of new stoves, the spiral brick packing can be built up right from the bottom of the stove, with a consequently much reduced overall height of such stoves. Tests have proved that a stove with an overall height of 55 ft. and fitted with spiral bricks alone is as efficient as a 95-ft. stove of the same diameter, fitted with the ordinary checker brickwork. Spiral bricks are in use in a number of plants in the United Kingdom, and the results obtained by their use at the Corby plant of Lloyds Ironstone Co. are given.

Checker Work for Chambers of Regenerators. W. Tafel. (Stahl und Eisen, 1929, Vol. 49, Mar. 14, pp. 355-356). Various arrangements of packing regenerator chambers are shown. Two methods are shown in which the riser bricks are set at an angle of 45° instead of vertically, a horizontal course being laid on each course of sloping bricks. By this arrangement a gain of some 20 per cent. in heating surface is secured. The ordinary ratio of heating surface to weight is 25.1 sq. m. per ton, but with sloping bricks the ratio may be increased to 31.7 or even to 37.2, according to the thickness of brick employed. This advantage is however counterbalanced by certain drawbacks, and no particular economy is secured by the use of sloping bricks. Neither is there any advantage in the use of the Moll-Rhenania brick, which is curved, so that when courses of such bricks are built into a regenerator they give a passage of elliptical form alternating with one of 4 sides, all of which are convex. A curved brick stores and gives up no more heat than a flat one.

Insulation of Coke-Ovens and Blast-Furnace Stoves with Sterchamol. A. Killing and K. Theis. (Glückauf, 1928, Vol. 64, Nov. 3, pp. 1482-1487; Stahl und Eisen, 1929, Vol. 49, Jan. 17, pp. 65-72). In the construction of new coke-oven batteries and blast-furnace stoves or in reconstructing old ones it has become the general practice to insulate them to reduce the heat losses. The material used (in Germany) is almost without exception sterchamol, a natural infusorial earth occurring in Denmark, which can be pressed into bricks of varying porosity, and these when fired have a crushing strength of 170 to 1700 lb. per sq. in. Comparative temperature measurements made on the outside of heat-insulated coke-ovens, regenerators, and stoves, and on uninsulated plant are recorded.

In the coke-oven plant on which the tests were made the method of insulating was to build a casing of sterchamol brick, $4\frac{1}{2}$ in. thick, in between the firebrick lining of the regenerators and the oven walls and roofs, and the external casing of ordinary brick. In some cases a 9-in. thick casing of sterchamol brick was used. In the regenerators it was found that the heat losses were reduced by 48 per cent., using a $4\frac{1}{2}$ -in. thick casing of sterchamol, and by 68 per cent. with one 9 in. thick. The insulation on the oven roofs was not so effective on account of the iron fittings in the roofs. The heating efficiency of the insulated battery of 65 Koppers ovens was 65 per cent. compared with 60 per cent. in the uninsulated battery. The insulation also had a beneficial effect on the coke at the chamber ends, the amount of coke breeze being reduced to one-half of that coming from an uninsulated battery.

Blast-furnace stoves were tested in the same way. Using sterchamol bricks as an external covering for 60 per cent. of the surface, including the entire dome, the radiation and conduction losses sank from 6 to 2 per cent., and the yield of effective heat rose from 83 to 87 per cent. It is reckoned that this heat economy in the utilisation of the gas would repay the cost of insulation in eight months.

Refractories and Heat Insulation in Connection with Furnace Design.

G. A. Barker. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, May, pp. 851-858). It is shown that a thin furnace wall of insulating material will transmit less heat than a very much thicker wall of solid refractory material. Refractory cements and their function in cutting down heat losses and protecting refractory linings are discussed.

Value of Insulation in the Steel Plant. L. M. McMillan and J. D. Van Valkenburgh. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Dec., pp. 1560-1566). The authors review the various applications of heat insulation to furnaces and auxiliary equipment, such as blast-furnaces, hot-blast stoves and mains, open-hearth regenerators, and billet furnaces.

The Economics of Insulating Industrial Heating Equipment. J. D. Van Valkenburgh. (Fuels and Furnaces, 1929, Vol. 7, Jan., pp. 49-52, 69-70; Feb., pp. 277-282). The author discusses in a general way the insulation of ovens and furnaces, and points out with the aid of heat-loss charts the savings which may result from the use of various thicknesses of insulation.

Diatomite. V. L. Eardley-Wilmot. (Canadian Department of Mines, Mines Branch, 1928, Report No. 691). The occurrence, preparation, and uses of diatomite are described. Diatomite on account of its relatively low thermal conductivity is one of the best-known heat insulators over a wide range of temperatures.

The Heat-Insulating Properties of Aluminium and their Application. De Brian. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 413-417). The author reviews the principles relating to the transmission of heat and the calorific properties of aluminium; he describes the Alfol insulating system in which aluminium foil is used as the insulating medium, and touches on the use of aluminium paint.

FUEL.

PROPERTIES, PREPARATION, MANUFACTURE, AND USES.

FUEL TECHNOLOGY.

The Relation between the Content of Hygroscopic Water of Solid Fuels, their Nature and their Calorific Power. J. Guth. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 34-36). The following subjects are dealt with: Hygroscopic and accidental humidities; indications of hygroscopic humidity; the classification of coals; and the relationship between the hygroscopic water content and the gross calorific power.

The Various Methods for Calculating the Calorific Power of Solid Fuels. P. Jarrier. (*Chaleur et Industrie*, 1929, Vol. 10, Mar., pp. 107-112).

Determination of the Calorific Value of Gases by Means of a Graduated Flask and a Junker Calorimeter by Dr. Geipert's Method. (Gas- und Wasserfach, 1928, Vol. 71, July 7, pp. 660-661).

The Influence of Incombustible Constituents on the Temperature of Combustion of Gaseous Fuels. F. Schuster. (*Wärme*, 1928, Vol. 51, June 16, pp. 427-429).

The Principles of Gas and Fuel Engineering. D. J. Demorest. (Fuels and Furnaces, 1929, Vol. 7, Jan., pp. 73-76, 148; Feb., pp. 209-212; Mar., pp. 359-361; Apr., pp. 505-510). The first article is concerned chiefly with the origin and nature of solid fuels, particularly of coal and the various compounds of which it is composed. The second article deals with the formation of peat bogs and the process of coalification. The separation of the constituents in coal by extraction with organic solvents is also dealt with. The third article outlines the nature and origin of petroleum and natural gas. The fourth article covers the combustion of the simple fuels, also the chemical reactions of their combustion, and explains combustion calculations with typical problems.

Heat Economy. J. W. Reber. (Fuel Economist, 1928, Vol. 4, Nov., pp. 107-110; 1929, Jan., pp. 211-213; Mar., pp. 299-302). The first article consists of an outline of the different types of fuels. The physical and chemical principles of combustion are discussed in the following articles.

Fuels and their Combustion. R. Martin. (Chaleur et Industrie, 1929, Vol. 10, Feb., pp. 87-95; Mar., pp. 149-154). The object of this study is to permit the rapid solution by means of graphs of some of the problems concerning the combustion of fuels.

Turbulence and Vibrations in Combustion. J. Louis. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Nov., pp. 436-447). The author discusses the combustion of solid fuel, the influence of the temperature on viscosity and its application to the gases of combustion, combustion on a grate and gaseous combustion above the grate, eddying in the gaseous mixture, secondary air, and the burning of pulverised fuel. He describes the "Turbulateur" burner for pulverised fuel.

Combustion with Oxygen-Enriched Air. W. Gumz. (Feuerungstechnik, 1928, Vol. 16, Apr. 1, pp. 73-76; Apr. 15, pp. 88-90). The author discusses the enrichment of the air for combustion under boilers; the principal advantages to be obtained by its use are: diminution of the volume of waste gases; increase in the theoretical combustion temperature with a reduction of the effects of dissociation, due to the increase in the concentration of the dissociating gases; acceleration of combustion accompanied by a shortening of the flame, with a consequent improvement in the effectiveness of the fire-box; and increase in the radiation, following on the increased temperature and the greater concentration of CO_2 and H_2O which participate in the radiation. The author deals with various aspects of the subject, such as the effect on the amounts of heat transmitted by radiation and convection, the possibility of fusing the ashes, re-design of the fire-box, and the economic viewpoint.

The Sulphur Problem in Burning Coal. J. F. Barkley. (United States Bureau of Mines, 1928, Technical Paper No. 436). The subject is treated under the following headings: Sulphur forms in coal; furnace reactions in burning coal; effect of sulphur content on clinkering; sulphur in gases; and corrosion of equipment.

The Importance of the Inorganic Constituents of Coal in Fuel Technology. K. Baum. (Glückauf, 1928, Vol. 64, Dec. 29, pp. 1733-1741). The author discusses the composition of coal ash and the action of ash on the processes of coking and of combustion. Under the

latter heading he also deals with the older processes for the determination of the melting point of the ash. He then describes Bunte and Baum's new process for determining the melting point of ash; he reports results obtained and discusses the applicability of the process. He finally puts forward an explanation of the slagging of ash.

The Study of the Process of Ignition of Solid Fuels. H. H. Greger. (Brennstoff-Chemie, 1928, Vol. 9, July 15, pp. 232-234). A rapid method for the determination of the ignition temperature of "coked" fuels is described, and the influence of physical factors on that temperature is discussed.

Researches on the Ignition of Coal—The Ignition of Pure Carbon. L. Dunoyer. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 43-52).

Chemical Preparation of Mixtures of Air and of Combustible Gas, Vapours, or Droplets before their Combustion. A. Grebel. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Nov., pp. 418-434).

Contribution to the Study of the Reactivity of Fuels. Method for Measuring the Speed of Propagation of Combustion. C. Quillard. (Comptes Rendus, 1928, Vol. 187, July 9, pp. 122-124). The speed of propagation of active combustion in a vertical column of fuel may constitute a characteristic of the material which is easily determined and stands in direct relation with its behaviour in the gas-producer. Some of the fuel is placed in a quartz tube (diam. 20 mm.) arranged vertically over an iron sheet, forming a column about 30 cm. high. Combustion is effected by a measured stream of oxygen or air passed upwards through the tube. It was found that there was no relation between the ignition temperature and the speed of propagation of combustion. Coal submitted to combustion under these conditions was not completely burnt; after the extinction of the luminous zone, there remained a substance resembling the original fuel which could be made to undergo further combustion under the same conditions. Although the percentage of ash increased the coal burnt faster and faster; indeed, the speed of propagation of combustion attained to a value not usually observed with ordinary coals.

Reactivities of Solid Carbon in Fuel Processes. J. W. Cobb. (Lecture to the Institution of Chemical Engineers, Jan. 18, 1929: Gas Journal, 1929, Vol. 185, Jan. 23, pp. 222-225).

Coal Blending for Combustion. D. Brownlie. (Engineering and Boiler House Review, 1929, Vol. 42, Feb., pp. 400-401). The

importance of blending, American practice, and smoke abatement are briefly discussed.

The Consumption of Fuel in Metallurgical Works. L. Bassal and Rocaut. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 744-761).

Graphic Expression of Practical Industrial Thermal Balances. H. Carra and C. Ponson. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 449-466).

Developments in Steam Boilers and the Use of Steam. O. Köster. (*Stahl und Eisen*, 1928, Vol. 48, Oct. 25, pp. 1497-1505 ; Nov. 1, pp. 1537-1545). After reviewing the general engineering progress in the use of steam and design of steam boilers the author proceeds to describe the methods of construction and to illustrate a number of modern types of high-pressure boilers. Among these are the Garbe, Dürr, Büttner, Babcock-Wilcox, Combustion Engineering Co., Linke-Hofmann (for powdered coal-firing), Atmos, Sulzer (two-stage pressure), Benson (for powdered coal-firing), and a proposed boiler for blast-furnace gas-firing. The arrangements for powdered coal-firing are particularly discussed.

Boiler-House Operation. M. G. Wallace. (*Fuel Economist*, 1928, Vol. 4, Nov., pp. 77-79 ; Dec., pp. 129-131 ; 1929, Jan., pp. 181-183).

New Boiler-House and Power Plant. H. T. Watts. (*Blast-Furnace and Steel Plant*, 1929, Vol. 17, Jan., pp. 166-170). The power plant of the Gulf States Steel Co., Alabama, is described. The boilers are fired with a combination of blast-furnace gas and pulverised fuel ; the steam pressure is 400 lb. per sq. in., and the temperature of superheat is 700° F. (370° C.).

The Hagan System of Automatic Boiler Control. (*Engineering*, 1929, Vol. 127, Feb. 22, pp. 247-248).

Recent Developments in the Economical Generation of Steam by Blast-Furnace Gas. A. E. Leek. (*Proceedings of the Cleveland Institution of Engineers*, Session 1928-29, No. 1, pp. 12-36). In dealing with the economical generation of steam, the author points out the economies which can be effected by the introduction of supermisers in boiler plants. He describes an installation of supermisers where the boilers are fired with blast-furnace gas.

Supermiser Installation at Ellesmere Port. (*Engineering*, 1929, Vol. 127, Mar. 15, pp. 328-330). The general arrangement of the supermiser installation at Ellesmere Port Works of the Wolverhampton

Corrugated Iron Co., Ltd., is described and illustrated, including an illustration showing a diagrammatic section through the supermiser itself. The plant is designed for use with a battery of four 30 ft. by 9 ft. Lancashire boilers, of which three units are normally working. The capacity of the plant was made suitable for an evaporation of 30,000 lb. per hr. with steam at 160 lb. per sq. in. superheated 150° F., the feed-water inlet to the supermiser being at 120° F.

Steam Accumulator Installation at Steelworks. (Engineering, 1929, Vol. 127, Jan. 18, pp. 73-76). An illustrated account is given of the Ruths steam accumulator installation at the River Don Steelworks, Sheffield.

Constant Pressure Thermal Storage. E. G. Phillips. (Paper read before the Institution of Heating and Ventilating Engineers: Fuel Economist, 1928, Vol. 4, Dec., pp. 131-136). The Kiesselbach system of thermal storage is outlined and its advantages are discussed.

Results obtained with the Sack and Kiesselbach Steam Accumulator Installed at Differdange. Communication from the Fuel Department of the Differdange Works. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Nov., pp. 716-722).

Steam Accumulators. A. Beaurienne. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Nov., pp. 705-714). A general discussion of accumulators, such as those of Christians, Kiesselbach, and Ruths.

A General Account of Recent Progress in Industrial Heating. E. Damour. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 9-13).

Testing and Rating of Fuel-Fired Industrial Furnaces. W. C. Buell, jun. (Fuels and Furnaces, 1928, Vol. 6, Nov., pp. 1505-1510; Dec., pp. 1713-1714, 1720; 1929, Vol. 7, Feb., pp. 243-246; Mar., pp. 375-377; Apr., pp. 559-562, 571). A classification is given of the various methods of testing furnaces, and their use and relative values are pointed out. Determination of heat balances and the calculation of efficiency of furnaces, heat recovery, and heat generating apparatus are dealt with. The characteristics of the different fuels used for test purposes and the systematic recording of test data and charts are discussed in detail.

Tests on the Heating of a Continuous Furnace with a Mixture of Blast-Furnace Gas and Pulverised Fuel, with the Possibility of Continuing the Heating with Pulverised Fuel Alone. G. Rey. (Paper

read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 117-131). The author discusses the heating of continuous furnaces with a mixture of blast-furnace gas and pulverised fuel, and describes tests made and the results obtained at the Creusot Works.

Evolution in the Conception of Continuous Furnaces and the Method of Heating Them. A. Hirt. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 369-377).

Consumption of Fuel in Pusher Furnaces. M. Laffargue. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 379-383).

The Total Radiation of Solid Bodies. H. Schmidt and E. Furthmann. (*Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1928, Vol. 10, pp. 225-264). The authors discuss the theory of the measurement of radiation with reference to its dependence upon the angle of emission, and describe their experimental apparatus, procedure, and results. Total emissivity values are recorded for a number of metals and non-metallic materials, including iron, nickel, oxidised iron, and an aluminium paint. A comparison is made with Maxwell's theory.

The Transmission of Heat by Convection in Industrial Plants. A. Lévêque. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 397-409).

Heat Recovery by Air Preheaters. P. H. N. Ulander. (*Fuel Economist*, 1929, Vol. 4, Feb., pp. 231-235). It is shown how the efficiency of a heat recovery apparatus constructed to work on the counterflow principle varies with the ratio between the flue gas and air quantities (ϕ). Similar equations are valid for uni-flow and cross-flow. For modern pulverised fuel-fired boilers the method of introducing the air to the furnace and the adaptation of the mills to the use of preheated air should be given special attention. It is a problem of the greatest importance how to maintain a low first cost and obtain a high efficiency in a boiler-house. With feed-water heating by steam drawn from the main turbines this can only be attained by an efficiently and effectively working air preheater, which reduces the flue gas temperature by 300° to 500° F., or more. The ratio ϕ imposes definite limitations on the air preheater efficiency, and has, therefore, direct influence on the economies of the boiler-house.

Study of Reheating Furnaces with Recuperators in which Part of the Heating Gases are Deflected. J. Seigle. (*Génie Civil*, 1929, Vol. 94,

Jan. 5, pp. 7-12). Four systems of preheating air and gas are described : I., Simple recuperation ; II., Part of the gases are drawn off from the middle of the furnace and used in the recuperator ; remainder goes to the chimney. Less gas is used for preheating, but its temperature is higher ; III., Part of the burnt gases are drawn off close to the burners and are used in regenerators (Siemens system) ; IV., The gas is preheated in a recuperator, while the air is heated in separate Cowper stoves. The author makes a mathematical comparison of the types, and gives two examples of large furnaces operating on system III., one at Differdange and the other at Belval, Luxemburg.

Existence and Determination of an Economic Speed of Circulation of Gases in Surface Heat Exchangers. M. Véron. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 698-704).

Note on Metallic Recuperators and Apparatus for the Production of Hot Air. M. Choisy. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 695-697). The utilisation of the heat in waste gases and the calorisation (surface treatment of mild steel with aluminium) of metallic heat exchangers are discussed. The recuperator at the Conservatoire des Arts et Métiers is described.

The Winkler Recuperative Smoke Consumer. C. A. Winkler. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 499-501).

The Influence of Preheating on the Theoretical Temperatures of Combustion of Gaseous Fuels. F. Schuster. (*Gas- und Wasserfach*, 1928, Vol. 71, Aug. 4, pp. 759-761).

The Course of Gas and Air Temperatures in Heat Exchangers. K. Rummel and A. Schack. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Feb., pp. 473-479). The article is mainly mathematical, and the authors' work consists in having derived a number of formulæ for calculating the periodic mean temperatures of the waste gas and heated air, and the regularly varying temperature in the regenerator. The effect of sudden changes and of regular change in the heat throughput of regenerators and recuperators is studied, and the manner in which the equations are thereby affected is shown. Graphic representation of the formulæ is made.

The Theory and Application of Regenerative Principles in the Steel Industry. T. J. McLoughlin. (Paper read before the American Iron and Steel Institute, May 1929). Thickness of brick and area of openings, effect of increased checker depth, efficiency of regenerators, 1929—i. 2 s

heat balance of furnace and regenerator, air infiltration, effect of insulation, use of increased regenerator heating surface, distribution of waste gases and air in regenerator chambers, influence of reversal period, dust deposits, regeneration in blast-furnace stoves, regeneration application to soaking pits, and regenerator application to reheating furnaces, are discussed. In any metallurgical operation, and especially those in the course of which a combustible gas is evolved, those factors which determine the most efficient design of heat recovery apparatus are by no means constant. To show the variation in these factors a typical open-hearth heat made with by-product coke-oven gas was chosen, and observations made at 5-min. intervals. The fuel supply varied from 95,500 cu. ft. per hr. to 53,800 cu. ft. per hr. as a minimum.

Variation in the volume of waste gases at a temperature of 2800° F., the temperature at which the gases should enter the regenerative chamber of a well-built open-hearth furnace, varied from 3,600,000 to 4,800,000 cu. ft. per hr., although one peak ran up to 6,400,000 cu. ft. per hr. This gives some idea of the changes in velocity at the entrance to checker openings of a regenerator, and serves to explain some of the changes in air temperature encountered in successive cycles of regeneration.

Density of waste gases varied from 0.0114 to 0.0119 (at 1400° F.), and the mean specific heat of the waste gases while in the checker work (2800° to 1400° F.) varied from 0.230 to 0.246 B.th.u. These figures serve to illustrate the reasons for the ever-changing rate of heat transfer as well as the low rates of heat transfer in the lowest portion of the chambers.

In order to exemplify the extent to which regeneration can be carried, and to show its effect, three heat balances were made. The first was an actual balance taken on a tar-burning open-hearth furnace, which had a relatively small checker chamber and a high rate of fuel consumption per ton of steel. The second showed that if the furnace was producing at the same rate, but double the waste heat was being returned in preheated air, the fuel was reduced from 2473 lb. per hr. to 1489 lb. per hr. If the fuel consumption could be maintained at the original rate, the improved regenerator performance hypothesized in the second example would increase the rate of production 66 per cent. and reduce the fuel requirements 40 per cent. These figures are indicative of trend only, since all of this heat cannot be used with known refractories.

One of the most serious handicaps to the maintenance of high temperatures is air leakage. In an excellently working open-hearth furnace there is an average drop in temperature of 500° F. in the waste gases from the outgoing end of the bath to the entrance to the regenerative chamber. This is due to radiation from port ends and to dilution of the hot waste gas with cold air entering the furnace system. Dilution of 30 per cent. is commonly indicated by analyses of waste gases. This decreases the sensible heat nearly 20 per cent.

Calculated heat balances of an uninsulated open-hearth regenerative

chamber show the heat lost by radiation from a 13½-in. roof to be 1750 B.th.u. per sq. ft. per hr.

Studies of distribution of gas in the checker work indicate that faulty distribution even in a new chamber is responsible for a disappointingly low rate of heat transfer. To help to correct this situation the distance from roof to top of checker work should decrease with increasing distance from the furnace end; an opposite change should be made in the size of the passages below the checker work. Thus a uniform depth of checker brick is possible in a rectangular chamber—a circumstance which produces theoretically a uniform draught at the base of each vertical opening.

The Effect of the Dust Deposit on the Efficiency of the Heat Storage Capacity of Checkers. A. Schack. (*Archiv für das Eisenhüttenwesen*, 1928, Vol. 2, Nov., pp. 287–291). A series of mathematical calculations is made as to the quantity of heat exchanged between the brickwork of the checkers and the gases during the heating and cooling periods of furnace regenerators. It is first assumed that the heat exchanger is an ideal one, and that the alternating periods of storing heat and giving out heat proceed under perfect conditions, heat losses to the exterior being ignored. The effect of a layer of material which is a bad heat conductor and without capacity for heat storage is then considered, and under such conditions the heat transfer value of the heat exchanger is reduced by 19 per cent. by a layer 3-mm. thick. A distinction is drawn between actual weight of checker brickwork and effective weight. The thicker the bricks and the shorter the period of heating and cooling, the smaller is the proportion of effective brickwork to the whole. It may be calculated that in the case of steel furnaces the proportion of effective brickwork is 50 per cent. of the whole, while in blast-furnace stoves it may be 80 per cent. of the whole. In the discussion on the paper it was pointed out that the author's assumption that layers of dust were bad heat conductors, with no capacity for heat storage, was not quite tenable, since the dust was often of a composition that allowed a better conduction of heat than the firebrick itself. Its character was variable in this respect, but in any case the heat conductivity of the dust was higher than had been allowed for.

The Calculation of Heat Storers on the Basis of the Throughput of Heat. K. Rummel. (*Stahl und Eisen*, 1928, Vol. 48, Dec. 6, pp. 1712–1715). This is a mathematical calculation of the dimensions and weight of checkers of regenerator chambers based on the quantity of heat exchanged between reversals of the furnace. The calculations are based on formulæ already established for recuperators. It is difficult to make an accurate calculation of the correct thickness of the checker bricks to meet different conditions, and after giving various values from which to derive a formula, it is concluded that it is

uneconomical to go below 30 mm. ($1\frac{1}{4}$ in.) as a minimum or above 80 mm. ($3\frac{1}{4}$ in.) as a maximum thickness. The thickness can range between these two dimensions according to whether greater or less differences between the maximum and minimum temperatures of the gas are desired, and in any case the thicker the bricks the more costly is the construction of the regenerator. The passages should be as narrow as possible, consistent with their not being too easily choked. It is an advantage to have high and narrow chambers, as this allows a higher velocity of gas and air and a more rapid heat transference. The best method of packing has not yet been properly worked out. Grid packing to produce eddying increases the rate of heat transference, but it is not certain whether this advantage is discounted by the increased resistance to flow.

The Periodic Temperature Change in the Regenerator. A. Schack. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Feb., pp. 481-486). The author calculates the differential equations for the periodic temperature change in furnace regenerators. Proposals are made for the construction of regenerators with non-uniform heat storage capacity. In order to reduce the objectionable drop in temperature in the heated air on leaving the regenerator the upper part of the chamber is to be filled with checkers of a greater heat storage capacity than the checkers in the remainder of the space.

Heat Exchange in Regenerators. H. Hausen. (Zeitschrift des Vereines deutscher Ingenieure, 1929, Vol. 73, Mar. 30, pp. 431-433). The periodic temperature variations in regenerators are dealt with mathematically.

Contribution to the Calculations of Regenerators. D. Chernobaëff. (Journal of the Russian Metallurgical Society, 1928, No. 1, pp. 85-90). (In Russian.)

Gas Flow through Packed Columns. S. P. Burke and W. B. Plummer. (Industrial and Engineering Chemistry, 1928, Vol. 20, Dec., pp. 1196-1200). Results are reported of numerous tests on the pressure drop for air flowing at various rates through systems packed with spheres. Since both the exponent and the coefficient of the general expressions connecting gas flow and pressure drop vary continuously over the range from viscous to turbulent flow, it has been found desirable to adopt the procedure used by various authorities in treating the subject of gas flow in pipes, and to represent all cases by one general expression containing a variable coefficient, which may be represented by a smooth curve. This general expression for gas (or other fluid) flow through packed spaces is—

$$p/l = C \cdot \frac{p V^2 S}{f^3}.$$

The variable coefficient is a function of, and is plotted against, $\mu S/pV$. In use it is only necessary to evaluate $\mu S/pV$ for the given case, read off C , and apply the general equation, without consideration as to the character of the flow, since this is taken care of by the plot of C .

COAL.

Microstructure of New Zealand Lignites. W. P. Evans. (New Zealand Journal of Science and Technology, 1928, Vol. 10, Oct., pp. 177-190). The conclusion of a series of articles (*see* Journ. I. and S.I., 1928, No. II. p. 259). The present instalment completes the consideration of lignites subjected to the influence of igneous intrusions, and deals with lignites from the C. Brockley Mine, Pullwool Peak, Malvern Hills, North Canterbury.

The Microscopic Structure of Coal. M. Le Graye. (Revue Universelle des Mines, 1929, Series 8, Vol. 1, Jan. 1, pp. 17-21). The author discusses the various constituents of coal which may be recognised microscopically.

Application of X-Rays to the Control and Examination of Mineral Fuels. L. Dauvilliers. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 73-81).

The X-Ray Analysis of Coal: The Radiographic Variables and their Control. C. N. Kemp. (Transactions of the Institution of Mining Engineers, 1929, Vol. 77, pp. 175-185).

A Note on the Mineralogy of Coal, as Suggested by X-Ray Examination. H. Briggs. (Transactions of the Institution of Mining Engineers, 1929, Vol. 77, pp. 5-10).

The Appearance of Coals, Oil Shales, and Other Mineral Substances in Ultra-Violet Rays. H. Briggs. (Transactions of the Institution of Mining Engineers, 1929, Vol. 77, pp. 11-15). A table is given which sets forth the results of an inspection of a number of economic minerals and their associates, their colour in lump in daylight and under ultra-violet rays being stated in every instance, and the appearance of the streak (powder) in most cases.

The Microscopical Examination of Fine Coal-Cleaning Products by the Method of Relief-Polishing. E. Stach and F. L. Kuhlwein. (Fuel in Science and Practice, 1929, Vol. 8, Apr., pp. 191-198). An

English translation of an article which appeared in Glückauf, 1928, Vol. 64, June 23, pp. 841-845. (See Journ. I. and S.I., 1928, No. II. p. 258.)

The Maceration Method in the Microscopic Examination of Coal. H. Bode. (Fuel in Science and Practice, 1929, Vol. 8, Feb., pp. 86-90). An English translation of an article which appeared in Berg-Technik, 1928, Vol. 21, p. 205. The principle of the maceration method is described.

Constitution and Classification of Coal. A. C. Fieldner. (Fuel in Science and Practice, 1929, Vol. 8, Jan., pp. 36-54). Coal should be classified primarily on the basis of its intrinsic chemical and physical properties. These properties involve the origin, composition, and constitution of the coal. Use classification should be secondary to scientific classification and should be correlated with the scientific classification as far as possible. Scientific classification depends on two primary factors—first, the composition and type of the original coal-forming vegetation; and, second, the degree of metamorphism or coalification of the vegetable residue. The first factor is exemplified broadly in the type of the coal, as xyloid, canneloid, or boghead; the second factor in the progressive rank of the coal as expressed in the series from lignite to anthracite. The criteria to be considered for classifying under these two general factors are proximate and ultimate analyses, calorific values, microscopic examination, extraction with solvents, reaction with reagents, and destructive distillation.

The Constitution and Origin of Fibrous Coal. K. Patteisky and F. Perjatel. (Glückauf, 1928, Vol. 64, Nov. 10, pp. 1503-1512).

Some Physico-Chemical Properties of Coal and its Colloidal Structure. H. Winter. (Glückauf, 1928, Vol. 64, Dec. 15, pp. 1686-1687).

Studies in the Composition of Coal. The Rational Analysis of Coal. W. Francis and R. V. Wheeler. (Journal of the Chemical Society, 1928, Part II., pp. 2967-2978).

Studies in the Composition of Coal. The Active-Decomposition Point of Coal. R. Holroyd and R. V. Wheeler. (Journal of the Chemical Society, 1928, Part II., pp. 3197-3203).

Studies in the Composition of Coal. Plant Entities as Oil-Yielding Constituents. R. Holroyd and R. V. Wheeler. (Journal of the Chemical Society, 1929, Part I., pp. 633-641).

The Importance of the Phosphorus Contents for the Formation of Fusain. F. Buchler. (Glückauf, 1929, Vol. 65, Feb. 2, pp. 161-164).

After a reference to the more important previous experimental results, determinations of the phosphorus contents of fusain are recorded. It appears that the presence of phosphorus in the products of the coal-forming process is not due to later accidental deposits, but is due to the manner and intensity of the process itself. It is shown that the phosphorus content is of importance in explaining the actual formation of coal. Phosphates are absent: (1) when the coal-forming process has led to the formation of humic acids (durain and vitrain), and (2) when sulphuric acid in quantity sufficient to dissolve them has been liberated (strongly pyritic fusain). The presence of phosphoric acids in fusain indicates the occurrence of a condition of equilibrium during the coal-forming process, in which the hydrogen sulphide had sufficed to prevent the formation of humic acids. From the co-existence of fusain and primarily formed pyrites it is concluded that the formation of fusain is not dependent on external influences, but is the result of reducing conditions produced by the decomposition of the organic matter itself.

Heating Value of Coal in Nickel-Lined Bombs. A. E. Stoppel and E. P. Harding. (*Industrial and Engineering Chemistry*, 1928, Vol. 20, Nov., pp. 1214-1218). A rapid method has been developed for determining the amount of nickel dissolved in a nickel-lined bomb by action of the nitric and sulphuric acids resulting from the combustion. This method involves merely a titration of the bomb washings for free acid in the usual way by means of standard alkali and methyl-red indicator, followed by a continuation of the titration in hot solution with the same standard alkali solution to a second end-point, using phenolphthalein as indicator. The heat of solution of nitric acid on the bomb lining has been determined, and directions are given for making a correction for corrosion in determining the water equivalent.

A method is proposed for making a correction for corrosion in determining the heating value of coal, which involves merely a titration of the bomb washings for free acid, and for combined acid, and a knowledge of the total percentage of sulphur in the coal. Heating values obtained by this method agree within 0.3 per cent. of those determined on the same coal by means of a non-corrodible illium bomb for coals containing up to 9 per cent. sulphur.

The Chemical Utilisation of Coal. C. Berthelot. (*Mémoires de la Société des Ingenieurs Civils de France*, 1928, Vol. 81, Sept.-Oct., pp. 1105-1180; *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1928, Vol. 127, July-Aug.-Sept., pp. 822-854).

Second Progress Report of the Dominion Fuel Board, 1923-1928, Ottawa. This report reviews briefly the work of the Board, outlines the present fuel situation in Canada, and shows the possibilities for the more efficient and diversified uses of coal.

The Relationship between the Specific Gravity and Ash Contents of the Coals of Korea and Bokaro : Coals as Colloid Systems. L. L. Fermor. (Records of the Geological Survey of India, 1928, Vol. 60, pp. 313-357).

The Past, Present, and Future of Illinois Coals. S. W. Parr. (Paper read before the American Iron and Steel Institute, May 1929). A general discussion of the characteristic features and properties of Illinois coals.

The Grading and Sampling of Coal. N. Simpkin. (Paper read before the Manchester Geological and Mining Society, Nov. 13, 1928 : Colliery Guardian, 1928, Vol. 137, Nov. 16, pp. 1952-1953).

Spontaneous Combustion in Coal Storage Dumps. D. Brownlie. (Engineering and Boiler House Review, 1928, Vol. 42, Dec., pp. 281-284). A survey of the chemical reactions involved.

Spontaneous Combustion of Stored Coal. A. F. Ward. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 298-301). The causes leading to the ignition of bituminous coals in heaps are reviewed, and safeguards are suggested.

The Spontaneous Combustion of Semi-Coke from Brown-Coal ; Its Causes and Prevention. P. Rosin. (Fuel in Science and Practice, 1929, Vol. 8, Feb., pp. 66-78). An abridged English translation of an article which appeared in Braunkohle, 1928, Vol. 27, pp. 241-256, 282-292. There are three methods of cooling semi-coke so as to avoid spontaneous combustion : (1) Artificial ageing ; (2) treatment with carbon dioxide ; (3) addition of magnesium chloride or ammonium chloride to the coal. All three processes may be used in combination with each other. It is possible in this way to prevent the spontaneous combustion of brown-coal semi-coke and to remove the barrier which stands in the way of its industrial application.

Economics of Coal Production and Distribution. (Iron and Coal Trades Review, 1928, Vol. 117, Nov. 23, pp. 757-759). Summaries are given of three papers dealing with the economics of coal production and distribution presented to the Institute of Fuel, Nov. 1928. The production of coal is dealt with by G. Raw ; its proper preparation for the market by H. Louis ; and its marketing by R. Addy.

The Cost of Clean Coal. C. W. H. Holmes. (Gas World, 1929, Vol. 90, May 11, Annual Coal Supplement, pp. 16-18). Some notes are given on the relationship between the cost of production of clean gas coals and their ash contents.

The Preparation of Coal. H. Louis. (Paper read before the Institute of Fuel, Nov. 21, 1928 : *Colliery Guardian*, 1928, Vol. 137, Nov. 30, pp. 2163-2164).

Coal Used in its Raw State. W. J. Drummond. (Paper read before the North-East Coast Institution of Engineers and Shipbuilders, Jan. 11, 1929 : *Iron and Coal Trades Review*, 1929, Vol. 118, Jan. 18, p. 79). The subject is discussed under the following headings : Preparation of coal ; collection of dust in dry cleaning plants ; losses in coal cleaning ; pulverised coal ; pulverised fuel with high ash content ; and oil *versus* coal.

Progress in Coal Preparation during 1928. R. V. Wheeler. (*Iron and Coal Trades Review*, 1929, Vol. 118, Jan. 25, p. 120).

The Principles of the Cleaning of Coals. R. Lessing. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 37-41). The author discusses the importance of mineral matter in relation to the formation of coal, and its distribution according to size. In considering the cleaning of coal the influence of ash considered as inert matter is dealt with, and the specific advantages of its perfect separation are pointed out. The influence of catalysts on carbonisation is touched upon.

Pneumatic or Dry Cleaning of Dry Bituminous Coal. C. Enzian. (*Proceedings of the Engineers' Society of Western Pennsylvania*, 1929, Vol. 45, Feb., pp. 38-56).

New Processes for the Dry Preparation of Coal. W. B. Gutacker. (*Montanistische Rundschau*, 1929, Vol. 21, Feb. 16, pp. 81-86). The author classifies dry cleaning machines into three groups : (1) Classifying tables with steady or intermittent air-blast ; (2) machines in which advantage is taken of the action of centrifugal force and of frictional and elastic differences in the coal ; (3) appliances in which cleaning is carried out by the admixture of sand, air being blown through the mixture. Various machines are described.

The Screening of Small Coal. A. N. H. Slade. (*Colliery Engineering*, 1929, Vol. 6, Mar., pp. 101-104 ; Apr., pp. 132-133).

Coal Sizing with Revolving Screens. S. Austin. (*Colliery Engineering*, 1928, Vol. 5, Dec., pp. 485-486). Points in the design and maintenance of revolving screens are discussed, and particulars are given of capacities.

The Lockwood Dry Cleaning Process. A. Grounds. (*Fuel Economist*, 1928, Vol. 4, Nov., pp. 103-105).

The Bamag-Meguín Dry Coal Cleaning Process. (Iron and Coal Trades Review, 1929, Vol. 118, Jan. 4, pp. 13-14). The general plan of the Bamag-Meguín dry-cleaning table and the arrangement and methods of operation of the entire plant are illustrated. The results of tests on a demonstration plant are given.

Note on the Mechanical Preparation of Coal by Means of the Sutton-Steele and Steele Pneumatic Tables, and the Resulting Advantages. R. Genel. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 63-67). The following subjects are dealt with: The development of dry-cleaning in America and England, problems met with in pneumatic separation, the influence of the humidity of the coal, the collection and utilisation of dust, economic considerations. The Wye separator and its operation are described.

Methods of Control and the Regulation of Coal-Washers. P. Guinard. (*Revue de l'Industrie Minérale*, 1929, Feb. 15, pp. 207-215). The ordinary system of controlling coal-washers necessitates the making of a large number of assays for the ash contents—a slow process. The washing itself depends on the relation between the density of the coal and its ash contents, and the author applies this characteristic (the density) to the control of the washer.

Coal Washability Tests as a Guide to the Economic Limit of Coal Washing. G. S. Scott. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 159). The object of the paper is to show that the highest economic purity of washed coal can be determined from washability studies of the raw coal, costs of mining and washing coal, and data on the effect of ash and sulphur on the value of the coal for the particular use for which it is intended. The case of coal washed for the production of blast-furnace coke is used to illustrate the method of determination of what percentage, if any, should be rejected as impurity? The various factors entering into the problem may be listed as follows: (1) cost of mining; (2) cost of washing; (3) cost of transportation; (4) cost of coking; (5) value of by-products; (6) cost of taking care of coke ash in blast-furnace; (7) cost of taking care of coke sulphur in blast-furnace. The necessary computations are set forth, and the particulars are summarised in graphic form.

The Laws of Motion of Particles in a Fluid. R. G. Lunnon. (Transactions of the Institution of Mining Engineers, 1929, Vol. 77, pp. 65-75). The author deals with the general problem of the fall of particles of different diameters and densities in fluids of different densities, and shows the limitations of Rittinger's law.

Specific Gravity and Determination of the Ash Contents by Washing Tests. W. Gross. (*Kohle und Erz*, 1928, Vol. 25, June 3, pp. 415-427). The author describes an apparatus for the carrying out of washing tests in the laboratory.

The Theory of Coal Washing. A. France. (Paper read before the Second International Conference on Bituminous Coal, Nov., 1928; *Iron and Coal Trades Review*, 1929, Vol. 118, Feb. 1, p. 178). The principle of the Rheolaveur coal-washing system is described.

The Ekof Desliming Classifier. J. W. Wardell. (*Colliery Engineering*, 1928, Vol. 5, Dec., pp. 493-495). A description is given of the Ekof machine, which consists of a fine coal classifier and deslimmer. The advantages to be obtained with the use of this apparatus are enumerated.

Coppée Washing Plant at the Loanhead Colliery. W. Maclaren. (*Colliery Guardian*, 1928, Vol. 137, Dec. 7, pp. 2251-2255). An illustrated account is given of the general arrangement and operation of this new washery, together with particulars of operating results. The plant, which is designed on the Baum principle, has a capacity of 120 tons of small coal per hour.

The Norton Patent Automatic Washery. (*Colliery Guardian*, 1928, Vol. 137, Dec. 7, pp. 2265-2266). The Norton patent automatic coal washery, which is operated on the Baum principle, is described and illustrated.

A Description of the Opening of an Anthracite Colliery and the Installation of a Modern Washing and Cleaning Plant. J. D. Morgan. (*Proceedings of the South Wales Institute of Engineers*, 1929, Vol. 45, pp. 241-286). The layout and equipment of the washing and cleaning plant at the Emlyn No. 2 Anthracite Colliery are described and illustrated.

New Screens and Washery at Emlyn Anthracite Colliery. (*Iron and Coal Trades Review*, 1929, Vol. 118, Mar. 1, pp. 317-320).

A Note on Some Modifications Introduced into a New Washer at the Haute-Loire Coal Mines. M. Abel. (*Revue de l'Industrie Minérale*, 1929, Mar. 15, pp. 239-247). On starting up a rheolaveur at the mines it was found that an appreciable quantity of saleable products was being carried over with the slimes. The experiments carried out to discover the reason for this, and the manner of applying them in the actual washing, are described.

Notes on a Visit to the Belgian and Dutch Coalfields. F. N. Woodhead. (*Iron and Coal Trades Review*, 1929, Vol. 118, Feb. 1, p. 181). Brief particulars are given of the Lavoir vertical coal-washer.

Cleaning of Coal in the Bituminous Fields of Pennsylvania. J. B. Morrow and J. R. Campbell. (*Proceedings of the Engineers' Society of Western Pennsylvania*, 1929, Vol. 45, Feb., pp. 10-37). The authors list the various types of coal-cleaning equipment used in the bituminous fields of Pennsylvania, and show the potential coal-washing capacity of the various plants.

Pulverised Fuel in Industry and Electrical Generation. (*Fuel Economist*, 1928, Vol. 4, Nov., pp. 87-92). Character of coal and combustion, combustion of volatiles and fixed carbon, nature of coal as affecting combustion, burners, preheated air for combustion, coal drying, preheated air for coal drying, dust removal from dryer vents, furnaces for burning powdered coal, and effect of moisture content on combustion are discussed.

Further Points in American Pulverised Fuel Practice. (*Fuel Economist*, 1929, Vol. 4, Feb., pp. 242-246).

Improved Type of Grinding Mill for Pulverised Fuel Plants. (*Fuel Economist*, 1929, Vol. 4, Feb., pp. 239-242). A description is given of the Raymond-Lopulco mill.

Electro-Filters for Pulverised Lignite. (*Kohle und Erz*, 1928, Dec. 21, pp. 990-998). Electrical gas-cleaners for removing the dust from the waste gases from pulverised lignite dryers, and their operation are described.

The Goossens System of Powdered Coal-Firing. A. Grounds. (*Fuel Economist*, 1928, Vol. 4, Nov., pp. 73-75). The results are given of tests on the firing of boilers by the Goossens powdered coal system.

The "Unit" System of Pulverised Fuel for Collieries. R. B. Potter. (*Iron and Coal Trades Review*, 1929, Vol. 118, Jan. 25, p. 153). The advantages of the unit system are pointed out, and a table is given showing the collieries where plants have been installed.

Investigation of the Thermal and Operating Conditions of Mill Furnaces Fired with Powdered Fuel. H. Ditges. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Jan., pp. 415-424). The trials were conducted on a continuous furnace with a small combustion chamber and horizontal burners, the dimensions being length of hearth 9.5 m.,

width 3 m., area of cross-section 1.4 sq. m., useful hearth area 28.5 sq. m. The material heated consisted of mild steel billets weighing 55 kg., 3 in. sq., and 45 in. long. The drawing temperature was 1365° C. and the throughput per hr. was $3\frac{1}{2}$ tons. The consumption of fuel in the form of coal-dust was 418 kg. per hr., or 120 kg. (264 lb.) per ton of steel. The burners were of the flat type, and were adjustable to an angle of 10° with the horizontal. The combustion conditions were good, the flame not developing fully till it reached the hearth, and the combustion of the coal particles continued throughout the length of the chamber, on which account the waste-heat losses were rather high. The losses due to burning of the charge amounted to 2.3 per cent. The soaking effect was good, the billets being uniformly heated throughout by the time they were ready for drawing.

Pulverised Coal for Metallurgical Work. W. O. Renkin. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 75-76). The use of pulverised coal in reheating furnaces is discussed. The importance of proper drying of the coal and correct degree of fineness is pointed out. Continuous furnaces of the flat arch suspended roof type have shown marked improvement in efficiencies and increased output. In this type of furnace a gas velocity of 20 ft. per sec. can be maintained. One installation heating billets from $3\frac{1}{2}$ to $4\frac{3}{4}$ in. sq. in lengths up to 11 ft. shows an average fuel consumption of 220 lb. of pulverised coal per ton of billets. In malleable melting furnaces the relation between carbon taken up by the bath and the fineness and moisture content of the coal is shown by means of a graph.

Pulverised Coal-Fired Rotary Furnace for Malleable Cast Iron. H. Kalpers. (Iron and Steel Industry, 1929, Vol. 2, Apr., pp. 197-200). A translation of an article in which a description is given of the Brackelsberg pulverised coal-fired rotary furnace for the manufacture of malleable cast iron. The original article appeared in *Giesserei-Zeitung*, 1929, Vol. 26, Feb. 1, pp. 78-82.

New Designs of Coal-Dust Fired Furnaces in Ironworks. G. Kehren. (Stahl und Eisen, 1928, Vol. 48, Dec. 20, pp. 1769-1773; *Röhren-industrie*, 1929, Vol. 22, Jan. 3, pp. 6-10). For many years past trials with coal-dust firing have been carried on, with much success in the case of steam boilers, but with varying results in metallurgical furnaces. In fact, many disappointments have been experienced, probably for the reason that it was believed any rubbish, as long as it was black, could be ground and fired as coal-dust. It is now recognised that in selecting coal for coal-dust firing, just as much care must be exercised as in buying gas coal or producer coal. The coals for grinding should have as high a content as possible of volatile constituents, they should have a low ash, and should be dried before grinding till they contain not more than 0.5 per cent. moisture. The problem of transporting

coal-dust through pipe lines by air pressure is not yet fully solved; for instance, there is the difficulty of separating the air from dust at the delivery point. Coal-dust firing of soaking pits and reheating furnaces can readily compete with producer-gas firing on account of the high price of producer coal, but where long-distance gas is available, coal-dust can only compete if the price of the gas exceeds about $7\frac{1}{2}$ d. per 1000 cu. ft. (these conditions apply to Westphalia). Sectional drawings of soaking pits and reheating furnaces adapted for powdered coal-firing are shown.

Pulverised Coal-Fired Furnaces. G. Kehren. (Iron and Coal Trades Review, 1929, Vol. 118, Feb. 8, pp. 208-209). An abridged translation of the above article.

Controlling the Atmosphere in Malleable Annealing Ovens. W. F. Graham. (Paper read before the American Foundrymen's Association, Apr. 1929). The author describes a method of firing furnaces of the oven type using pulverised coal, in which some of the waste gases are returned to the furnace chamber.

Furnace Heating by Means of Pulverised Fuel. G. E. K. Blythe. (Paper read before the South Wales Section of the Institute of Metals: Foundry Trade Journal, 1929, Vol. 40, Feb. 21, pp. 147-150).

Use of Pulverised Fuel in Metallurgical Furnaces. G. E. K. Blythe. (Paper read before the Second International Conference on Bituminous Coal, Nov., 1928: Fuels and Furnaces, 1928, Dec., Vol. 6, pp. 1661-1664).

Utilisation of Rhenish Lignite in the Iron, Steel, and Metal Industry. H. M. Kaspers. (Archiv für Wärmewirtschaft, 1929, Vol. 10, Feb., pp. 57-61). An account is given of the use of pulverised lignite in heating, forging, annealing, and tempering furnaces.

Coal-Dust Firing for Boilers and Industrial Furnaces. H. Berg and E. Vogt. (Journal of the Institute of Fuel, 1929, Vol. 2, Apr., pp. 240-257). The authors deal with the utilisation of coal-dust for the firing of mill and forge furnaces. Different types of furnaces are illustrated and described. A list is appended of the furnaces installed on the Continent, particulars being included of furnace output per hour, type of fuel, consumption of fuel, and type of pulverising installation.

Developments in the Use of Pulverised Fuel for Steam Raising. D. Brownlie. (Iron and Coal Trades Review, 1929, Vol. 118, Jan. 25, p. 121).

Progress in Pulverised Coal Application. E. H. Tenney. (Paper read before the American Society of Mechanical Engineers: Blast-Furnace and Steel Plant, 1929, Vol. 17, Mar., pp. 439-444). Operating results obtained with the use of pulverised fuel at the Cahokia Power Station, St. Louis, are presented.

Pulverised Fuel for Boiler Firing. J. C. Brand. (Paper read before the Institution of Engineers and Shipbuilders in Scotland, Mar. 12, 1929: Iron and Coal Trades Review, 1929, Vol. 118, Mar. 22, pp. 433-434). The Brand system of pulverised fuel firing is described, and its application to marine and Lancashire boilers is dealt with.

Pulverised Fuel Tests on Lancashire Boilers. (Engineer, 1929, Vol. 147, Mar. 15, p. 304). Particulars are given of the results of trials of two Lancashire boilers fitted with the Brand system of pulverised fuel firing.

Unit Pulverisers for Steam Generation. J. Blizzard. (Blast-Furnace and Steel Plant, 1929, Vol. 17, May, pp. 717-720). A discussion of some of the problems involved in the use of the unit system for pulverising coal for firing under boilers.

The Modern Use of Pulverised Fuel in Power Stations. R. A. Chattock. (Paper read before the Institution of Electrical Engineers, 1929: Colliery Guardian, 1929, Vol. 138, Apr. 26, pp. 1617-1620).

Pulverised Fuel Installation at the Wallasey Generating Station. (Engineering, 1929, Vol. 127, Apr. 26, pp. 511-513). The plant described consists of two 50,000-lb. boilers equipped with pulverised fuel firing on the unit system. The pulverisers used are of the Simon-Carvés type.

Synthracite. E. Gevers-Orban. (Revue Universelle des Mines, 1929, Series 8, Vol. 1, Feb. 15, pp. 93-98). "Synthracite" is the name given to the product of the Charbonnages Espérance Bonne-Fortune at Montegnée-Liège. Ovoids of anthracite dust bonded with pitch only are unsatisfactory in use, but by heating them slowly to about 800° C. they become very serviceable; the ovoids described weigh 38 grm. each and contain 6 per cent. of volatiles, but by raising the temperature slightly the volatiles can be reduced to 1½ per cent., producing a true metallurgical coke, graphitic and very hard. The plant consists of two vertical continuous retorts designed by M. J. Piéters; the tops are open and the bottoms are water-sealed. The heating flues pass up the longer sides, and the distillation products are withdrawn through openings in the shorter sides. The first cost of the plant, the thermal balance, the refractories, and other matters are discussed.

Briquetting. J. Bing. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 21-29). The author discusses the manufacture of fuel briquettes, tests for pitch, substitutes for pitch, and the briquetting of lignites and semi-cokes. He gives statistics of the briquetting of coal.

Tests on the Auto-Agglomeration of French Lignites. A. Moreau. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 30-32). Chemical, physico-chemical, and physical tests are discussed.

Tests on the Transportation of Dry Lignite. E. Rammler. (Braunkohle, 1928, Vol. 27, Dec. 22, pp. 1147-1152). The transportation and storage of dry lignite were investigated from the point of view of the fire risk.

PEAT.

Peat Considered as a Fuel. F. Le Monnier. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 54-61). The author discusses the classification of peat bogs, conditions of exploitation, the drying of peat, the colloidal character of peat, peat as an industrial fuel, a thermal balance for peat, the distillation of peat and peat coke.

COKE.

The Coke-Oven Industry in 1928. C. P. Finn. (Iron and Coal Trades Review, 1929, Vol. 118, Jan. 25, pp. 121-122).

Recent Developments in the Utilisation of Bituminous Coal. (Mechanical Engineering, 1929, Vol. 51, Jan., pp. 65-69 ; Feb., pp. 142-146). A review of the important points in the preparation, treatment for extracting liquid fuels and other by-products, utilisation for power generation, &c., brought out at the Second Conference on Bituminous Coal at Pittsburgh.

The Becker Coke-Oven Plant. (Colliery Guardian, 1929, Vol. 138, Apr. 12, pp. 1421-1427). **Becker Coke-Oven Plant for the Nunnery Colliery Company, Sheffield.** (Engineering, 1929, Vol. 127, Apr. 12, pp. 453-456). **Becker Coke-Oven Plant at the Handsworth Works of the Nunnery Colliery Company, Ltd.** (Iron and Coal Trades Review,

1929, Vol. 118, Apr. 12, pp. 530-533) **Britain's First Becker Coke-Oven Installation.** (Gas Journal, 1929, Vol. 186, Apr. 10, pp. 85-89). **Great Britain's First Becker Coke-Oven Plant.** (Gas World, 1929, Vol. 90, Apr. 6, Coking and By-Product Section, pp. 41-45). Illustrated particulars are given of the layout and equipment of the Becker coke-oven plant at the Handsworth Works of the Nunnery Colliery Co.

The By-Product Coke Plant of the Steel Company of Canada at Hamilton, Ontario. J. F. Slee. (Engineering Journal, Jan., 1929: Iron and Steel of Canada, 1929, Vol. 12, Feb., pp. 40-44). The plant is described. There are two batteries of 40 ovens each of the Wilputte regenerative type; they measure 37 ft. 3 in. long, 10 ft. 5½ in. high, 16½ in. wide at the pusher end and 19 in. wide at the coke end, and hold about 13 net tons of coal each. The operation of the ovens is described, and details concerning auxiliary plant are given.

Coke Works of the Carnegie Steel Company. F. F. Marquard. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., p. 77). Brief notes on the Clairton by-product coke plant, said to be the largest and most complete works of its kind. There are 1482 Koppers and Becker type ovens, with a coking capacity of 31,000 tons of coal a day. The plant uses only Pittsburgh high-volatile coal. The coke is quenched by an intermittent water spray, which keeps the moisture content within narrow limits; waste water contaminated with phenol is used in a closed system for spraying; in this way pollution of the river is avoided.

By-Product Coke Plant at Hamilton. C. L. Haldeman. (Blast-Furnace and Steel Plant, 1929, Vol. 17, May, pp. 688-690). An illustrated account is given of the coke-oven plant of the Hamilton Coke and Iron Co., Ohio, which has a normal capacity of about 1250 tons of coal. Both blast-furnace and foundry coke are produced. The coke-oven battery consists of 45 Becker ovens, each having a capacity of 14.8 net tons. The oven chamber is 14 in. wide at the pusher side and 16 in. wide at the coke side, 12 ft. 6 in. high, and 40 ft. 8 in. long. Three charging holes are provided. Oven gas is used for heating, although provision is made for the use of either producer- or blast-furnace gas.

Experiences with Modern Coke-Ovens in the Ruhr District. W. Gollmer. (Stahl und Eisen, 1929, Vol. 49, Jan. 31, pp. 129-138; Glückauf, 1929, Vol. 65, Jan. 26, pp. 108-121). At the beginning of 1926 there were 140 coke-oven plants in operation in the Ruhr district, with 16,200 ovens. These, for the most part, obsolete plants could produce about 28,000,000 tons of coke a year. Under a rationalisation scheme, which was adopted towards the end of 1926, 2770 new ovens had been built at 32 plants by the beginning of 1928. Of these 32, 18 plants were entirely new, and consisted of 1710 new ovens. The
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other 14 were plants which were enlarged by the addition of 1060 new ovens. Including four other large plants, there are now altogether 36 plants on a large scale with just under 7000 ovens, producing 24,900,000 tons of coke a year, of which 15,300,000 tons is produced in the 2770 new ovens. This scheme of reconstruction practically revolutionises the economy of coke manufacture, and all older plants must of necessity soon shut down, for these 36 large plants with their 7000 ovens produced, in 1927, 91 per cent. of the total coke made in the Ruhr district. The oven with narrow chamber has been abandoned, because, in spite of its high efficiency on account of the short coking time, consumers did not like the small hard fingery coke which it produced. For large batteries a width of 450 mm. has been generally adopted, while some have been built with a width of 500 mm., and one is now designed with a width of 530 mm. The main departure from previous practice is, however, in the height of the chamber. These are now made 4 m. and even up to 6 m. in height, or nearly 20 ft. The coking time in such ovens is 18 hr. with an output of 20 tons of coke per heat, the yield being 78 per cent. The throughput per 24 hr. is up to 27·8 tons. A number of technical details are described and illustrated. In general, these do not differ greatly from former practice, but apparatus and transport arrangements are on a larger scale. The coking cost per ton of coke in a modern plant producing one million tons yearly amounts to 4·4s., and by sale of power gas this is reduced to 3·02s. per ton. The actual prime cost per ton of coke produced is 33·2s., and the receipts from sale of coke, gas, tar, and by-products are 38·7s. per ton.

Modern Cokeries in the Ruhr District. W. Gollmer. (*Iron and Coal Trades Review*, 1929, Vol. 118, Mar. 8, pp. 364–365; Mar. 15, pp. 389–390). **The Modern Coking Plants of the Ruhr District.** W. Gollmer. (*Fuel Economist*, 1929, Vol. 4, Mar., pp. 305–308, Apr., pp. 355–359). Translations into English of the above paper.

Modern Mining Methods in the Ruhr Coalfield. R. C. Smart. (*Colliery Guardian*, 1928, Vol. 137, Nov. 16, pp. 1947–1953). Notes are given of the coking and by-product plants at different collieries in the Ruhr district, including a detailed description of the coking plant at the Köln-Neuessen Colliery, Altenessen.

The New Central Coke-Oven Plant at the Emil Mine, Essen-Altenessen. R. Gau. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Mar. 30, pp. 437–440). The author first indicates the differences between the developments that have recently been made in American and German coke-oven plants of large size. He then describes and illustrates that at the Emil mine. It consists of 3 batteries, each of 39 large ovens, with a total throughput of 600,000 tons per annum. Each oven is 12 m. long, 3·6 m. high, 475 mm. wide at the middle,

the pusher end being 60 mm. narrower than the coke end. The charge is 17·8 tons of coal with about 12 per cent. of moisture, and the coking period is 20 to 21 hr. From 2400 tons of coal the 117 ovens produce 1650 tons of coke. The structure and operation are described, and details of by-product recovery, &c., are given.

A Modern Coke-Oven. K. Falk. (Feuerfest, 1929, Vol. 5, Feb., pp. 15–21). The author reviews briefly recent developments in the design of coke-ovens, and describes the "grouped flue" regenerative coke-oven of the Hinselmann Co., Essen, which is intended for firing by either rich or poor gas at will. The oven is built up on a ferro-concrete "base-plate," which is supported on piers; the valves controlling the heating of the ovens are situated in the cool space under the base-plate. The oven walls rise directly from the base-plate, and their lower parts serve as dividing walls for the regenerators situated under the ovens and the hot flues. The regenerators are built in two groups of different sizes, those lying under the hot walls being arranged as small preheaters for each individual combustion point. The large regenerators serve only for preheating the air; when poor gas is used the small regenerators preheat it, but with rich gas in use they preheat the air. The large regenerators have only one sole flue which carries away the waste gases or furnishes the air for combustion, but the small individual regenerators are alternately connected in groups of four to one or other of the two sole flues under them. The operation of the plant is described in detail, and the advantages are enumerated.

The New Coke-Ovens of Dr. C. Otto & Co. G. Lorenzen. (Feuerfest, 1929, Vol. 5, Feb., pp. 26–29). The ovens built by the firm in 1923 were about 10 to 11 m. in length, 3 m. high, and capable of containing 9 to 10 tons of dry coal; in the last two years the dimensions have grown to about 13 m. and 4·5 m. respectively, and the capacity to about 19 tons. This alone represents about 100 per cent. increase in throughput, and as the time of heating has been decreased the throughput has been actually increased even more. This reduction of heating time has been attained by a new system of heating. Instead of the gases burning in the vertical flues on one side of the oven, and the waste gases passing through the horizontal flues to the vertical flues in the opposite wall, and so to the regenerators, the vertical flues in each wall are arranged in pairs, each pair being joined by a short horizontal flue at the top ("twin-flue system"); in this way the full heat is applied to both sides of the oven at once. By making suitable arrangements rich or poor gas may be utilised. Details and results obtained at the company's experimental plant at Dahlhausen, and at other plants built for other companies, are given.

Machinery for Coke-Oven Plant. F. G. Smith. (Paper read before the Cleveland Institution of Engineers, Feb. 11, 1929: Iron and Coal

Trades Review, 1929, Vol. 118, Feb. 15, pp. 239-240). The author outlines recent developments in the design of machinery used in connection with regenerative coke-ovens. Brief notes are given of a coal charging larry, a combined coke pusher and leveller, and a combined coke guide and door extractor.

Development in Simplex Coke-Oven Design. (Iron and Coal Trades Review, 1929, Vol. 118, Jan. 11, p. 89). The arrangement of the flues in the new Simplex coke-oven provides for the continuous heating of all the flues as against periodical heating of half the flues. Illustrated particulars are given of the methods adopted.

Adapts Balanced Draft Coke-Oven for Firing Low Heat Value Gases. (Iron Trade Review, 1929, Vol. 83, Nov. 15, p. 1250). A cross-section is shown of a balanced draft coke-oven which has been adapted for the use of blast-furnace or producer gas. One set of regenerators is used for preheating the air and the other set for preheating the gas. When it is desired to use coke-oven gas the two sets of regenerators connected in parallel are both used for preheating the air.

Ways and Means of Attaining an Even Distribution of Heat in the Vertical Direction in Coke-Oven Walls. R. Gau. (Feuerfest, 1929, Vol. 5, Feb., pp. 29-32). The many systems of obtaining a regular distribution of heat from the bottom to the top of coke-oven walls—Collin's alternate heating from the top and from the bottom, Otto's twin flues, Still and Wolter's step-wise heating, Koppers' narrow-top oven, Becker's system of mixing air for combustion with waste gases and alternate heating of one or the other wall, the Lothringen Mining Company's circulating system—are reviewed. The "Kogag" oven of the Koksofenbau und Gasverwertung A.G. is described. In this oven the cross-sectional area of the flues is decreased in steps towards the top by bellying the faces of the walls dividing the flues; the gases are thus brought into more intimate contact with the walls of the oven and travel more quickly. The increased thickness of the dividing walls also serves to accumulate more heat, which is available when the direction of the gas flow is reversed.

Coke-Oven Practice and Developments in Bulk Carbonisation. W. H. Blauvelt. (Paper read before the Fuel Conference of the World Power Conference, 1928: Iron and Coal Trades Review, 1928, Vol. 117, Dec. 28, p. 937). The author reviews developments in coke-oven practice in the United States. The largest ovens now operating have a capacity of 19 to 20 tons per charge. The batteries have been increased to contain as many as 60 ovens, and the coking time has been greatly reduced; 1 in. per hr. is regarded as a very moderate speed. One plant has a record of two months' operation at more than 1.3 in. per hr. This increase per unit of plant capacity and per man-hour has to a large

extent off-set the greatly increased cost of construction and wage rate since the early days of the industry. One of the characteristics of recent coke-oven operation in the manufacture of blast-furnace coke is the production of a free burning coke having a well-developed cell structure, more reactive to the oxygen of the blast than was formerly thought practicable. The large crucibles and steep bosh walls of the modern American furnaces have made the use of these more reactive cokes possible, and permit the use of many coals heretofore thought undesirable.

The Efficiency of a Coke-Oven. G. E. Foxwell. (Gas World, 1928, Vol. 89, Dec. 1, Coking Section, pp. 138-140; 1929, Vol. 90, Feb. 2, Coking Section, pp. 18-21). The factors to be observed for the efficient operation of coke-ovens and the methods for determining and expressing the thermal efficiency are discussed.

The Coking Process. J. Roberts. (Colliery Engineering, 1929, Vol. 6, Mar., pp. 91-92; Apr., pp. 129-131). The coking phenomena of coal are briefly explained under the following headings: the coking stages, formation of coke in stages; controlling the behaviour of the binder; influence of the ash on the binder; facilitating the advance of the binder and sources of energy loss.

Contribution to the Study of the Mechanism of the Carbonisation of Coal. E. Audibert. (Revue de l'Industrie Minérale, 1929, Jan. 15, pp. 151-187).

The Effect of Pre-Oxidation on the Primary Distillation Products of Coal. Part V.—Examination of the Cokes and Gases Obtained by Distillation at 600°. J. T. Donnelly, C. H. Foott, and J. Reilly. (Journal of the Society of Chemical Industry, 1929, Vol. 48, Feb. 8, pp. 38-40T).

Note on the High-Temperature Carbonisation of Coal. Langroyne and Boulin. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 153-158). The authors discuss the extension of the range of coking coals, modern coke-oven plants, coke-oven gas, and town gas.

Calculation of the Time of Carbonisation according to the Modifications Introduced into the Ovens. W. Lohrisch. (Feuerungstechnik, 1928, Vol. 46, June 15, pp. 133-136).

Moisture in Coal and Coke and its Influence on the Carbonising Process. E. Dubois. (Gas- und Wasserfach, Aug. 18, 1928; *abridged translation*, Gas Journal, 1928, Vol. 184, Dec. 26, pp. 848-849).

The Preparation and Coking of Fine Grain Coal in the Light of Petrographic Knowledge of Coal. F. L. Kühlwein. (Glückauf, 1929,

Vol. 65, Mar. 9, pp. 321-329 ; Mar. 16, pp. 363-371 ; Mar. 23, pp. 395-405).

Production of Foundry Coke. A. E. Taylor. (Paper read before the Institute of British Foundrymen : Foundry Trade Journal, 1929, Vol. 40, Apr. 18, pp. 289-291). The effects of temperature of carbonisation, oven width, size and screening of coke, and cleaning and blending of coal on the properties of the resulting coke are discussed. The qualities desired in a foundry coke are a high calorific value and hardness to stand the severe abrasion with the pig iron. A dense, non-friable, well-burnt, correctly sized coke is therefore considered necessary.

The Supervision of the Thermal Operations of Coke-Ovens. W. Liesegang. (Feuerfest, 1929, Vol. 5, Feb., pp. 33-37). Various appliances for measuring temperatures, gas pressures, volumes of gas flowing, for analysing waste gases, &c., are described and illustrated.

Volatile Matter and Coke Yield. (Iron and Coal Trades Review, 1928, Vol. 117, Dec. 21, pp. 907-908). A digest is given of the discussion which took place before the Cleveland Section of the Coke-Oven Managers' Association on December 6, on the relationship between volatile matter of coal as determined in the laboratory, and the yield of coke from the oven.

The Influence of Inorganic Materials in Lignite Carbonisation. A. W. Gauger and D. J. Salley. (Paper read before the Second International Conference on Bituminous Coal, Nov., 1928 : Fuel in Science and Practice, 1929, Vol. 8, Feb., pp. 79-85). Inorganic materials may exert a specific effect on the structure of the char as well as on the yield of char, tar, and gas from the carbonisation of Velva lignite. It seems essential that one must be cautious in predicting the effect of ash material from results of experiments of this nature without being certain that the added material is chemically identical with the inherent mineral matter in the coal in question. Hydrated aluminium chloride, sulphate, and nitrate, magnesium sulphate and chloride, and strontium chloride alter the structure of the char produced, yielding a hard pseudo-coke differing materially from the soft powdered char of the untreated coal, whereas the anhydrous salts produce soft, fine char. Hydrated ferric chloride increases the yield of char at the expense of the tar. Sodium carbonate decreases char and tar yields and increases gas yields. Silica is without effect. A mechanism for the formation of pseudo-coke is suggested.

The Withdrawal of the Gas from Coke-Ovens and its Automatic Regulation. C. Arnu. (Technique Moderne, 1928, Vol. 20, July 1,

pp. 452-458). The author describes modern arrangements for regulating the pressure of the gas in the hydraulic main for the purpose of adjusting the calorific power of the gas to the value desired.

Drying and Heating a Coke-Oven Battery by Liquid Fuel. F. White and W. H. Russell. (Paper read before the Coke-Oven Managers' Association, Jan. 23, 1929: *Iron and Coal Trades Review*, 1929, Vol. 118, Feb. 1, pp. 183-184). The authors describe the method of heating up the coke-oven battery at the South Yorkshire Chemical Works and the results obtained.

Chemical Utilisation of Coke-Oven Gas. Valette. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 319-327). The author discusses the separation of the constituents of the gas and the complete transformation of the products of the distillation of coal into chemical products.

The Dry Quenching of Coke. J. B. Fortune. (*Fuel Economist*, 1928, Vol. 4, Nov., pp. 95-100). Particulars are given of some installations in operation for the dry cooling of coke.

The Dry Quenching of Coke. D. W. Wilson. (Paper read before the Second International Conference on Bituminous Coal, Nov. 1928: *Gas Journal*, 1928, Vol. 184, Dec. 19, pp. 792-794). A discussion of the results obtained from the operation of a Sulzer coke quenching plant.

Dry Coke Cooling by the Sulzer Process at the Oswald Street Gasworks, Burnley. J. H. Clegg. (Paper read before the Manchester District Institution of Gas Engineers, Dec. 14: *Gas Journal*, 1928, Vol. 184, Dec. 19, pp. 785-790).

National Interest in the Low-Temperature Distillation of Fuels. C. Roszak. (*Mémoires de la Société des Ingenieurs Civils de France*, 1928, Vol. 81, Sept.-Oct., pp. 1064-1104; *Chaleur et Industrie*, 1929, Vol. 10, Feb., pp. 55-63; Mar., pp. 119-128). The author defines the distinctions between low- and high-temperature carbonisation. He discusses the chemical composition of fossilised solid fuels and the products of low-temperature distillation. He reviews the points of view from which various countries regard low-temperature carbonisation: the production of petrol interests countries which have no oil wells; in England the smokeless fuel obtained is the important consideration; Germany favours the process for increasing the value of the poor quality coals available; other countries, which do not produce coal, regard it as a means of utilising fuel more rationally. All four points of view are of interest to France. The Rolle, Tozer, Salerni,

Cantiény, Pintsch, and Merz and Maclellan low-temperature distillation processes are described, followed by a description of the Hereng system. One form of the Hereng system is intended to be installed in front of boilers. The plant consists of a drier and a distillation chamber. The chain grate of the boiler is extended forward under both the distillation chamber and the drier. The coal passes by gravity through the drier, falls on to the chain grate, and is carried into the distillation chamber; the coke passes into the boiler fire-box without stirring or disturbance of any sort, and is then burnt in the ordinary way. In one form of plant, the distillation gas is partially burnt in the distillation chamber to provide the necessary heat, the excess of unburnt gas passing on into the boiler fire-box. In another variation the rich gas is collected; the heat for distillation is supplied by circulating in a closed circuit some of the rich gas suitably preheated. In other types the coke is not burnt at once, but is dry-quenched and disposed of as a domestic fuel or as pulverised fuel.

Fuels Obtained by the Treatment of Coal. W. T. K. Braunholtz. (Paper read before the North East Coast Institution of Engineers and Shipbuilders, Jan. 11, 1929: *Iron and Coal Trades Review*, 1929, Vol. 118, Jan. 18, pp. 79-81). The subject is dealt with under the following headings: coking industry; coke and coal gas; low-temperature carbonisation; low-temperature retorts; value of by-products; hydrogenation of coal; process of continuous hydrogenation; and other synthetic methods of producing fuel oils.

Low-Temperature Carbonisation in 1928. S. R. Illingworth. (*Iron and Coal Trades Review*, 1929, Vol. 118, Jan. 25, p. 122).

Low-Temperature Carbonisation of Coal. S. W. Parr. (Paper read before the Second International Conference on Bituminous Coal, Nov., 1928: *Industrial and Engineering Chemistry*, 1929, Vol. 21, Feb., pp. 164-168).

Low-Temperature Carbonisation—Developments at British Collieries. D. Brownlie. (*Iron and Coal Trades Review*, 1929, Vol. 118, Apr. 5, pp. 493-494).

Fuel Developments and the Training of Fuel Technologists. J. W. Whittaker. (*Iron and Coal Trades Review*, 1929, Vol. 118, Mar. 1, p. 325). The author surveys the economic possibilities of low-temperature carbonisation.

The Distillation of Coal from the Point of View of Fuel Economy. G. Cantiény. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 178-191). High- and low-temperature distillation, the

quality of the products and the advantage of their use are discussed ; the construction and arrangement of a distillation plant is described.

The Adaptation of Coke-Oven and Gasworks Processes to Low-Temperature Carbonisation. J. S. C. Deville. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 173-177). A discussion of low-temperature carbonisation, semi-coke, the operation of the retorts, tar and its evaluation, the gas, and motor spirit.

Low-Temperature Carbonisation of Blended New Zealand Coals. W. G. Hughson. (New Zealand Journal of Science and Technology, 1929, Vol. 10, Feb., pp. 263-274). The Gray-King method of assay was used to determine the behaviour of New Zealand coal when carbonised at a low temperature. Brown-coals yielded on an average 10.59 cwt. of carbonised residue, 27.58 gal. of oil, 51.53 gal. of liquor, 3.3 lb. of ammonium sulphate, and 3841 cu. ft. of gas per ton of coal ; the average bituminous yield was 14.23 cwt. of residue, 37.42 gal. of oil, 9.23 gal. of liquor, 1.24 lb. of ammonium sulphate, and 3530 cu. ft. of gas. Low-temperature carbonisation of unblended New Zealand coals leaves either a non-adherent non-coking residue or a much swollen mass of friable coke, according to whether the coal is brown or bituminous. By carbonising suitable blends at 600° C., semi-cokes of good texture and hardness were obtained.

The Present Condition of Low-Temperature Carbonisation in Germany. R. Heinze and A. Thau. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Apr. 20, pp. 524-530).

Low-Temperature Distillation. J. A. de Grey. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 243-252). The following aspects are dealt with : the importance of low-temperature distillation ; technical conditions ; the present state of the question in Germany. Various furnaces are described.

Present State of the Technique of Low-Temperature Carbonisation of Coals and Lignites. C. Berthelot. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 253-254). Low-temperature carbonisation in the Saar district is discussed.

Low-Temperature Carbonisation of Coal from the South Russian Basin. A. Chakhno. (*Chimie et Industrie*, 1929, Vol. 21, Jan., pp. 32-34).

The Problem of the Low-Temperature Distillation of Coal and the Utilisation of the Semi-Coke. A. Kling and D. Florentin. (Paper

read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 217-220).

Low-Temperature Distillation of Coals and in Particular Bituminous Coals. A. Léauté. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 208-216). After a reference to work carried out by the U.S. Bureau of Mines on similar material, the author describes his own experiments. He discusses the nature of the coals and of the agglutinants used, and gives details of the carrying out of an experiment for each of the groups.

Present State of the Low-Temperature Carbonisation of Coal and Lignite in Various Countries. D. Brownlie. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 222-233). An enumeration and discussion of various low-temperature carbonisation processes.

Low-Temperature Carbonisation of Schist. The Situation in Various Countries of the World. D. Brownlie. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 234-242). The importance of schist deposits is pointed out, their exploitation in various countries is discussed, and processes for treating it are enumerated.

Low-Temperature Carbonisation of Pulverised Coal. F. M. Gentry. (*World Power*, 1929, Vol. 11, Feb., pp. 151-154 ; Mar., pp. 251-254). The first article deals with the general processing of coal for the extraction of its by-products and the production of smokeless fuel. The author deals more particularly with those methods of low-temperature carbonisation in which heat is transferred to the pulverised particles by means of radiation and conduction. The second article deals with the heating of pulverised coal by convection heat transfer. Illustrated particulars are given of the following retorts for pulverised coal : Lewes ; Pinet-Debout ; John ; Trent ; Kuhn ; McEwen and McEwen-Runge.

The Bussey Coal-Distillation Process. H. B. Cronshaw. (*Engineering*, 1929, Vol. 127, Mar. 29, pp. 409-411). Illustrated particulars are given of the Bussey plant for the manufacture of smokeless fuel, oil, and gas, which is in course of erection at Glenboig, near Glasgow. The plant will have a throughput of 500 to 600 tons of coal per day, and a daily output, when working at capacity, of approximately 300 to 400 tons of semi-coke, 15,000 gal. of crude oil, and 15,000,000 cu. ft. of gas. The Bussey retort is of the stationary vertical shaft and internally heated type. The process is continuous, and the charging and discharging operations are automatic and adjustable.

Low-Temperature Distillation by Means of Waste Gases. F. A. Oetken. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Feb. 16, pp. 229-232). The Lurgi low-temperature distillation process, in which heat is supplied to the coal by the passage of heated waste gases through it, is described. The heating of the charge and the cooling of the semi-coke is performed by circulating some burnt gas in a closed system, the heat taken up by cooling the coke being utilised to supply some of the heat for the charge in the retort. The amount of waste gas introduced into the distillation gases is small, so that the latter are still combustible. Direct and indirect methods of heating the charge are discussed.

The Lurgi Carbonisation Process applied to Lignite. F. A. Oetken and O. Hubmann. (*Braunkohle*, 1928, Vol. 27, Dec. 8, pp. 1097-1104).

The Lurgi Method of Low-Temperature Carbonisation. (*Colliery Guardian*, 1929, Vol. 138, Apr. 5, pp. 1337-1338).

Coal Distillation. (*Colliery Guardian*, 1929, Vol. 138, Apr. 5, p. 1341). Brief particulars are given of the Freeman modified low-temperature distillation process.

The Gas Light and Coke Company's Experimental Carbonisation Plant at Fulham. (*Engineering*, 1929, Vol. 127, Mar. 1, pp. 260-261). The equipment of this plant is described and illustrated.

Low-Temperature Carbonisation Process. P. Dvorkovitz. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, vol. 9, Oct., pp. 193-199). After an historical note, the experimental plant at Slough and its objective are described; the English point of view regarding the carbonisation of coal and its economic and national importance are discussed.

Low-Temperature Carbonisation. (*Colliery Guardian*, 1929, Vol. 138, Mar. 15, pp. 1021-1023). The general layout and equipment of the Coalite plant at Barugh, near Barnsley, are described and illustrated.

Economic Utilisation of Fuel in the Production of Electricity. R. P. Sloan. (Paper read before the Fuel Conference of the World Power Conference, 1928: *Iron and Coal Trades Review*, 1928, Vol. 117, Nov. 16, pp. 721-728). The paper is devoted chiefly to a description of the low-temperature carbonisation plant at Dunston-upon-Tyne.

The Dunston Coal-Distillation Plant. (*Engineering*, 1928, Vol. 126, Dec. 21, pp. 787-788).

Low-Temperature Carbonisation Plant at Dalmarnock. J. B. C. Kershaw. (*Engineer*, 1928, Vol. 146, Dec. 14, pp. 651-652). The

financial results of the actual working of the McLaurin low-temperature carbonisation plant at the Dalmarock Gasworks for the two years ending May 21, 1928, are presented.

Low-Temperature Carbonisation Plant. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Apr., pp. 576-578). **Largest Distilled Coal Plant in the World.** (Coal Age, 1929, Vol. 34, Apr., pp. 229-230). An illustrated account is given of the K.S.G. carbonisation plant recently erected at New Brunswick, N.J., which has an annual carbonising capacity of 250,000 tons. The constructional details of the retort are shown.

A Chemical Study of Low-Temperature Tar. G. T. Morgan, D. D. Pratt, and J. Ross. (Journal of the Society of Chemical Industry, 1929, Vol. 48, Feb. 8, pp. 29-34T). Low-temperature tar contains a notable proportion of resinous products, and these have been divided into four groups: neutral resins, phenolic resins or resinols, acidic resins or resinic acids, and basic resins or resinamines. These resinous products, which can be isolated from tar by simple processes, are likely to find industrial applications. An extract of tar in aqueous caustic soda contains, in addition to crystallisable phenols, resinols, and resinic acids, a considerable portion of neutral resins. Extraction of true phenols including resinols is preferably effected by the use of a caustic soda-brine reagent. The crystallisable phenols when distilled with water under reduced pressure and subsequently fractionated *in vacuo* show little or no tendency to redden either alone or in emulsions. The isolation of original constituents of low-temperature tars, and particularly of the four groups of resinous products, has been rendered practicable by the use of the solvent method employed at comparatively low temperatures. Owing to this avoidance of high temperature other decomposable constituents of the tar, such as waxes and higher aromatics, have been obtained in appreciably larger yields.

Aqueous Liquors from Low-Temperature Carbonisation of Coal. G. T. Morgan, D. D. Pratt, and A. E. J. Pettet. (Journal of the Society of Chemical Industry, 1929, Vol. 48, May 3, pp. 89-93T). Aqueous liquor from the carbonisation at low temperature of a non-coking coal and aqueous distillate from the tar obtained in that carbonisation have been examined by a process of continuous extraction by ether. The total ammonia content, which in the case of the liquor is 0.55 per cent., is increased threefold in the distillate. The sulphur content is increased slightly in the distillate as compared with the liquor, and on acidification by mineral acid the liquor yields hydrogen sulphide, and the distillate sulphur dioxide and elemental sulphur. Aniline, pyridine, and α -picoline have been isolated from both the liquor and the distillate. Resinamines occur to a small extent in the bases from the liquor.

Formic, propionic, *n*-butyric, and *n*-valeric acids have been identified as derivatives, and acetic, oxalic, and resinic acids have been isolated from the acids of the liquor. Phenol occurred to the extent of 0.15 per cent. of the liquor and 0.2 per cent. of the distillate, whilst pyrocatechol was present in amount corresponding to 0.1 per cent. of the liquor, but was only detected in traces in the phenols from the distillate. A new class of resin (resinic acids) has been characterised and isolated from the phenols of the liquor, whilst resinols mixed with resinenes occurred in the viscous portion of the phenols from the distillate.

Composition of Tar from Low-Temperature Carbonisation of Utah Coal. R. L. Brown and R. N. Pollock. (Industrial and Engineering Chemistry, 1929, Vol. 21, Mar., pp. 234-238).

Contribution to the Production of Low-Temperature Tar. G. Kroupa. (Montanistische Rundschau, 1928, Vol. 20, Dec. 16, pp. 693-696). The author discusses the importance to Austria of the production of low-temperature tar by the distillation of brown-coal, and describes his patent oven for attaining this end. It consists of a tall structure, at the top of which is a chamber in which the material is dried; from here it travels over a series of sloping hearths until it reaches the bottom, where it is discharged into a cooling space. The sloping hearths are hollow, and are heated with a mixture of air and gas in such a way that the material in its downward passage is raised to a steadily increasing temperature.

Assessing the Value of Coking Coals. G. W. J. Bradley and R. A. Mott. (Paper read before the Midland Institute of Mining Engineers, Dec. 11, 1928: Iron and Coal Trades Review, 1928, Vol. 117, Dec. 14, pp. 867-868). The authors review methods for determining the coking property of coals, particularly those used in the fuel technology laboratories of Sheffield University. The contraction and swelling ranges of different coals are shown.

Properties of Coking Coals and their Behaviour on Coking. P. Damm. (Fuel in Science and Practice, 1929, Vol. 8, Apr., pp. 163-177). A translation of an article which appeared in Glückauf, 1928, Vol. 64, Aug. 11, pp. 1073-1080; Aug. 18, pp. 1105-111. See Journ. I. and S.I., 1928, No. II. p. 273.

Clean Coke and Its Value. R. A. Mott. (Fuel in Science and Practice, 1929, Vol. 8, Mar., pp. 123-132). When mechanical coal cleaning was first introduced the coals were washed to a lower ash content than is customary in modern times, but at the expense of losing considerable quantities of coal in the refuse. The practice of increasing the yield at the expense of a high ash content of the washed coal became widely adopted in the war years, and immediately afterwards

when the price of coal rose enormously. The ash content rose to over 14 per cent. and resulted in big increases in fuel consumption at the blast-furnaces. A table is given in which the fuel consumption in cwt. per ton of pig iron (and the amount of ore used) is calculated for different districts in the United Kingdom for the period 1912-1919. The results obtained by different investigators for the difference in coke consumption per ton of pig iron when using cokes of different ash contents are reviewed. The results of large-scale tests by Derclaye and Gill, and of the calculations by Deladrière and Evans show that the saving in coke consumption per ton of pig for every 1 per cent. by which the ash content is reduced may be summarised as follows :

	Cwt.
Derclaye	0.47
Gill	0.44
Deladrière	0.35
Evans	0.33-0.48

or an average of approximately 0.4 cwt. per 1 per cent. of ash. The financial saving has been estimated by the following investigators :

	Pence.
Derclaye (adapted)	8
Louis (on basis of Gill's results)	9
Thau	9
Lilot	8
Lewis (adapted)	12

From these figures it may be assumed that a reduction of 1 per cent. of ash in coke is worth at least 6d. per ton of coke to the iron maker. The washing of slurry is dealt with, and the Rheolaveur slurry washer, concentrating tables, and froth flotation units are briefly outlined. The advantages of clean slurry are also discussed.

The Choice of Cokes for the Blast-Furnace. E. C. Evans. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 162-171). The author discusses the correlation of blast-furnace operating results, the influence of coke quality on blast-furnace working, coke-testing, structure, combustibility, reactivity, density, porosity.

Some Varieties of Carbon and their Reactivity. R. V. Wheeler. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 160-161). The author discusses the different aspects of coke, the varieties of carbon resulting from the decomposition of methane, and their reactivity.

Improved Method for Determining the Porosity of Cokes. G. A. Brender à Brandis. (*Het Gas*, 1928, Vol. 48, Sept. 15, pp. 390-394).

Contribution to the Question of the Properties of "Foundry Coke."

B. Osann. (*Die Giesserei*, 1929, Vol. 16, May 3, pp. 421-422). The shatter test gives a measure of the suitability of coke for cupola use; other tests, even the reactivity tests, do not. The reason why Upper Silesian coke is unsuitable for the cupola is explained.

The Physical Properties of Foundry Coke.

H. V. A. Briscoe. (Paper read before the Institute of British Foundrymen: *Foundry Trade Journal*, 1929, Vol. 40, Apr. 25, pp. 307-308).

Smokeless Domestic Fuels.

J. Roberts. (*Colliery Engineering*, 1928, Vol. 5, Dec., pp. 483-484). A brief discussion of the characteristic properties of various forms of semi-coke.

GASEOUS FUELS.

The "Roubaix" Crusher-Gas-Producer for the Utilisation of Residues from Combustion. (*Génie Civil*, 1929, Vol. 94, Apr. 27, pp. 410-411). The apparatus briefly described in this article is intended to make use of the unburnt fuel which may pass through a furnace grate; it is attached directly to the chain grate housing so as to take advantage of the sensible heat in the ashes as well as of their fuel contents. The ashes are discharged from the chain grate directly into the vertical water-cooled body of the producer. At the bottom are arranged two crushing rolls; beneath them is an inlet for an air-blast, and below that an arrangement for removing the spent ashes. The crushers revolve slowly; the cold blast moving upwards keeps them cool, and ensures the complete combustion of any combustible material remaining in the ashes. The combustible gas produced passes directly upwards into the main fire-box, where it is burnt, so adding its heating value to that of the fuel burnt on the chain grate. The ashes, after passing through the crushers, drop into water; in this way sufficient steam is added to the air-blast before it passes through the column of ashes. The energy absorbed in operating the crusher-gas-producer, including the blower, does not exceed 0.5 per cent. of that recovered by the appliance. A further advantage of the apparatus is that the chain grate may be more completely covered, right up to its end; in this way the total excess air is reduced, because with its use there is not the same disadvantage in allowing unburnt material to pass over with the ashes.

Note on Some Improvements Introduced during the Last Few Years in Industrial Gas-Producers and on the General Installation of these Producers. M. Guérin. (Paper read before the Second Congress on

Industrial Heating, Paris, June 23, 1928 : Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 278-281).

Operating Conditions of Producers in which the Ashes are Melted, and Comparative Thermal Balances. Dessemond and Mayençonne. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : Chaleur et Industrie, 1928, Vol. 9, Oct., pp. 272-275). The present working conditions of the producers, in which the ashes are fused, at the Achille gas generating station are described, and the thermal balances and efficiencies of the various producers are compared.

Source of Errors in the Carbon Balance. Wehrmann. (Gas- und Wasserfach, 1928, Vol. 71, Dec. 29, p. 1253). In determining the thermal balance of a gas-producer it is customary to withdraw the gas for the analysis of CO_2 after the washer, and to assume that the amount retained by the washer amounts to 0.3 to 0.4 per cent. The author shows that this estimate is too low, and that the figure should be 0.6 to 0.7 per cent.

Study of Gasification and the Practical Operation of Gas-Producers. H. Guillon. (Chaleur et Industrie, 1928, Vol. 9, Dec., pp. 580-587; 1929, Vol. 10, Jan., pp. 37-43). The author studies the subject under the following headings : Theoretical study of gasification ; incomplete combustion of carbon ; speed of reaction ; influence of temperature on states of equilibrium ; injection of steam into gas-producers ; fusion of the ashes ; theoretical study of the decomposition of steam ; mechanism of the decomposition in producers ; formation of CO or CO_2 ; different qualities of mixed gas ; quantity of steam decomposed and conditions to be aimed at in a producer ; and the gasification of solid fuels—namely, wood and its derivatives, lean coals and cokes, and fat coals.

The Gasification of Steam-Dried Köflach Coals in Revolving-Grate Gas-Producers. L. A. Richter. (Braunkohle, 1928, Vol. 27, Sept. 15, pp. 850-857).

The Use in Gas-Producers of Wood Distilled at Low Temperatures. G. Dupont, J. L. Lussand, and J. Allard. (Annales de l'Office National des Combustibles Liquides, July-Aug., 1928 ; Génie Civil, 1929, Vol. 94, Jan. 26, pp. 92-93). The results of experiments on the low-temperature distillation of various woods are reported. The apparatus used is described. Up to 275°C . dissociation is feeble ; at 300° to 350° a violent exothermic reaction occurs. At the lower temperatures the gases contain 75 per cent. of CO_2 and 25 per cent. of CO, together with the air occluded in the wood. During the exothermic reaction the CO_2 reaches only 60 per cent. and the CO attains to 40 per cent., its maximum. Above 350° to 400°C . the gases evolved are rich in hydro-

carbons with high calorific power. Experiments to determine the optimum temperature were also made. By the use of wood heated between 100° and 290° C., particularly between 275° and 290°, the theoretical maximum calorific efficiency in relation to the original wood is attained, and the gas produced has a maximum calorific power.

Operating Tests on a Producer Intended for Use with Wood Charged with Peat. A. Lemmonier. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 289–292). The author describes the operation of a peat-charged producer, discusses granulated peat from Liesse (Aisne), and gives the results of tests for efficiency.

New Gas-Heated Installations of Small Dimensions, intended to Furnish Producer-Gas from Various Fuels. W. Kirnich. (*Feuerungstechnik*, 1928, Vol. 16, July 1, pp. 149–154).

Improved Means of Producing Gas for Steelworks. (Fuel Economist, 1928, Vol. 4, Nov., p. 75). Particulars are given of the Duffield gasification process. The coal is pulverised to about 200 mesh, and part of the sensible heat of the gas made later in the process is used by transference for heating air to 200° C. for a preliminary oxidation of the powdered fuel. The object of this preheating is to prevent pastiness occurring in the next process, which consists of passing the powdered fuel down a spiral channel in which it is subjected to a temperature of 500° C. by means of extracting further heat from the gasification and transferring it to some of the gas which has been cleaned of the volatiles. This heated gas is blown through the oxidised coal during its course of travel, and by contact at the temperature of 500° C. distils off and picks up the volatile constituents of the coal. The gas from this chamber is then treated for the extraction of the combustibles and volatiles, after which it is returned to the main. The heat of the volatiles is transferred by a heat exchanger to the air used in the combustion chamber. The powdered coke from which the volatiles have been distilled is then used as far as required for combustion and gasification, and any surplus is agglomerated in a special press to a condition resembling lump coal. The residual volatile of this material is up to 10 per cent.

Investigation of a Cottrell-Möller Plant for Separation of the Dust from the Waste Gases of Open-Hearth Furnaces. E. Göbel. (*Stahl und Eisen*, 1929, Vol. 49, Jan. 10, pp. 33–37). The factors which influence the successful operation of an electric gas-cleaning installation are, as is well known, the speed of flow of the gases, the temperature, degree of moisture, voltage at the electrodes, size of dust particles, amount of dust in the uncleaned gas, and the chemical composition of the dust. In the trials undertaken, it was endeavoured to

ascertain the influence of each one of these factors on the efficiency of the process. The highest degree of cleanliness was obtained with the maximum voltage possible (50,000 v.), the lowest speed of flow of the gas, and the lowest possible temperature (114° C.). The degree of moisture at temperatures above the dew point appears to exercise little influence. The best results appear to have been obtained with a rate of flow of gas of 1.25 m. per sec. The dust from the gases of the furnaces under trial contained from 31 to 95 per cent. zinc oxide, and 48.9 down to 2.1 per cent. lead oxide.

Electro-Filters. F. Moureau. (*Revue Universelle des Mines*, 1929, Series 8, Vol. 1, Feb. 15, pp. 106-109). The Cottrell and Siemens electrical gas-cleaners are briefly described, and their application to various industries is discussed.

On the Mathematical Theory of the Cottrell Electric Precipitator. A. W. Simon. (*Iron and Steel Engineer*, 1929, Vol. 6, Apr., pp. 143-146).

The Cleaning of Industrial Waste Gases. F. Croset. (*Arts et Métiers*, 1929, Vol. 82, Apr., pp. 151-153). The electrical precipitation of dust from waste gases is described.

The Purification and Cleaning of Waste Gases. R. Toutain de Bussy. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 486-492). After reviewing the various types of gas-cleaners, the author describes the "film gas-cleaner," in which the gases are brought into contact with films of liquid such as oil; he gives test results, and discusses the recovery of the oil by filter-press, centrifuge, and solvent.

Recent Progress in the Industrial Cleaning of Works Waste Gases. Pauthenier. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 495-497).

Petroleum Wash-Oil Thickening in the Scrubbing of Coke-Oven Gas. H. M. Ullman, D. S. Chamberlin, C. W. Simmons, and M. A. Thorpe. (*Industrial and Engineering Chemistry*, 1929, Vol. 21, Apr. 1, pp. 313-314). A high boiling petroleum oil is used in the counter-current absorption of light oils from coke-oven gas in scrubbing towers. With continued use the wash-oil increases in gravity from 0.834 to 0.90, and contains a suspension which, when settled out, does not materially affect the gravity of the oil. This process is called thickening. With thickening, a wash-oil reduces in absorption capacity, and the accumulation of the suspended material presents mechanical difficulties throughout the entire system. The authors have investigated the primary

cause of such thickening, which is shown to be the direct result of a tar, or a tar constituent in a finely divided form suspended in the gas.

Long-Distance Gas Transmission. K. Traenckner. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Apr. 20, pp. 517-523). The author first discusses the importance of long-distance gas transmission as a means of conveying energy and the development of the industrial use of gas in America, and compares the cost of transmission with that of electricity. He then deals with the choice of suitable diameters for the pipes and their influence on the transmission costs, and a large number of other points of technical and economic importance.

Long-Distance Transmission of Coke-Oven Gas in Germany. A. Pott. (Paper read before the Second International Conference on Bituminous Coal, Nov., 1928 : *Gas World*, 1929, Vol. 90, Mar. 2, Coking Section, pp. 30-34).

Application of Centrifugal Machines to Various Gas-Transmission Problems. P. Faraggi. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 300-308). The author touches on the following subjects : the evolution of centrifugal machines for the transmission of gas ; exhausters for coke-oven gas ; tar cleaners ; driving the exhausters ; boosters for coke-oven gas ; the transmission of steam and gas at high temperatures.

Co-Ordination between Blast-Furnaces, Coke-Ovens and Open-Hearth Furnaces. C. Berthelot. (Paper read before the Fuel Conference of the World Power Conference, Sept., 1928 : *Iron and Coal Trades Review*, 1928, Vol. 117, Nov. 16, pp. 717-718). The author shows how by proper co-ordination between the various processes in an iron and steel works, it should be possible to produce about 1 metric ton of finished steel with 1.75 ton of good coking coal, besides obtaining valuable by-products. His estimates are based on his own work, and the researches of leading French and German authorities, as well as on a thorough inspection of plants in the Ruhr coalfields, where very satisfactory results are being obtained with a new type of coke-oven.

Heating with Blast-Furnace Gas. (*Iron Age*, 1929, Vol. 123, Mar. 7, pp. 664-666). **By-Product Ovens are Fired with Blast-Furnace Gas.** (*Iron Trade Review*, 1929, Vol. 84, Mar. 7, pp. 644-645). The arrangements for heating coke-ovens at the plant of the By-Products Coke Corporation, Chicago, are described. The coke-ovens are in two batteries of 55 each. The blast-furnaces are situated a mile from the ovens and the gas is transported in a 60-in. pipe. The gas is cleaned by passing through a dry dust-catcher, a Roberts and Kennedy dry

cleaner, a Brassert washer, and a Theisen washer. The gas is stored at the coking plant in a 2 million cu. ft. dry gas-holder, having a working pressure of 8 in. of water. The results of trials show that blast-furnace gas gives a more uniform distribution of heat, resulting in the production of a better coke.

The Industrial Uses of Gas. F. W. Goodenough. (Journal of the Institute of Fuel, 1929, Vol. 2, Apr., pp. 258-292). The advantages of gas for industrial heating are pointed out, and numerous installations are illustrated, including melting and heat-treating furnaces.

The Use of Gas in General Engineering Works. A. Docking. (Gas World, Industrial Gas Supplement, 1928, Vol. 1, No. 2, Nov. 17, pp. 7-11). The many uses to which gas may be put in small and medium-sized general engineering shops—melting, case-hardening, heat-treating of tools, expanding and shrinking on bosses, drying ladles, skin-drying loam moulds, floor-drying sand moulds, heating core and mould stoves, &c.—are enumerated and discussed.

Industrial Heating by Gas. (Engineer, 1929, Vol. 147, Feb. 15, pp. 190-191). Notes are given of gas-heating installations at the works of G. Kent & Co., Luton, and at the Basingstoke works of J. I. Thornycroft & Co. A description is also given of the Premix gas and air mixer, which maintains a constant quality of mixture and pressure regardless of the working conditions.

Relative Cost and Value of Fuels. E. A. W. Jefferies. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Nov., pp. 1446-1448, 1453). The relative values of various fuels and their costs for use in open-hearth and heating furnaces are compared, and the advantages of producer-gas are clearly brought out. It is shown that after making full allowance for all expenses of gasification and paying \$3.75 per ton for coal the average fuel cost in an open-hearth using 450 lb. of coal per gross ton of steel is \$1.00. This corresponds to using 38.6 gal. of fuel oil, costing in the furnace \$3.09; the equivalent amount of coke-oven gas is 9818 cu. ft., costing (at 25 cts.) \$2.55.

The Production and Utilisation of Gas in German Ironworks. H. Bansen. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 309-320). The subject is dealt with under the following heads: Blast-furnace gas, its production, cleaning, distribution, combustion, and utilisation for heating blast; power generation in steam boilers and waste-heat boilers, transmission, and blowing; furnaces and methods of firing with gas; coke-oven gas; sale of surplus gas. Concerning combustion of blast-furnace gas the author points out that whereas with fluctuating gas pressure an air excess of 25 to 30 per cent. is usually allowed, with a constant gas pressure a 10 per cent. air excess is sufficient. A 10 per cent. excess reduces the carbon dioxide

by 1 per cent., the temperature of combustion by 50° , the furnace temperature by 30° to 40° , and the furnace efficiency by 3 to 10 per cent. The quantity of waste gas is increased by about 5 per cent., but since its temperature is increased by 30° to 50° , its volume is increased by 10 per cent. or over. By preheating and by intimate mixing of the air and gas streams by means of the torsion burner, the zone of combustion is shortened and more perfect combustion is attained with an increase in flame temperature. For instance, in stoves and boilers using old-type burners with large currents of air and gas the zone of combustion extends 10 to 20 m. before the carbon monoxide is completely burnt, and the heat developed does not exceed 500,000 kg. cal. per hr. per cu. m. of combustion space. With greater subdivision of gas and air flues in furnace ports the heat developed rises to 1,000,000 kg. cal. per hr. per cu. m., and with torsion burners it rises to 15,000,000 kg. cal. per hr. per cu. m., 50 per cent. of the combustion taking place at the tip of the burner and complete combustion within a distance of 1 m.

Certain Principles in the Extended Utilisation of Blast-Furnace Gas.

O. R. Rice. (Iron and Steel Engineer, 1929, Vol. 6, Apr., pp. 176-181). The author discusses the principles that apply to the utilisation of blast-furnace gas in the different departments of a steelworks, and considers the value of the gas as fuel and the cost involved in rendering it suitable for different purposes. Underfiring of coke-ovens offers the most attractive application of blast-furnace gas. Its advantage is contingent upon market possibilities outside the plant for selling the coke-oven gas thereby released to industrial and domestic uses. There is a very high ratio between the value of the blast-furnace gas and the cost of conditioning it for oven use. Use of blast-furnace gas in steel heating furnaces is pyrometrically practicable and financially attractive. A safe ratio exists between the fuel value of the gas and the conditioning cost. Blast-furnace gas is good fuel under boilers. However, its return in boiler coal replacement value is not apt to be very high, and judicious consideration must be given to the question of the cost involved in conditioning the gas. In the heating of blast-furnace stoves, blast-furnace gas finds its most essential and profitable utility.

Use of Blast-Furnace and Coke-Oven Gas in Open-Hearth Furnaces.

F. E. Leahy. (Paper read before the American Iron and Steel Institute, May 1929). Standard type open-hearth furnaces require structural alterations, particularly below floor-level, to render them suitable for the use of blast-furnace gas. With producer-gas the tar and soot carried in help to keep the flues and checker chambers gas-tight, but with clean blast-furnace gas the checker chambers require sealing to avoid leakage of gas through the walls and roof. The installation of a pre-heater using waste gases for heating the blast-furnace gas to 1200° F.

or higher, and then enriching with cold coke-oven gas at the furnace ports would do away with the necessity of gas-tight chambers. Both checker chambers could then be used to preheat the air. A theoretical temperature of 3200° F. can be attained by either preheating the blast-furnace gas to 1075° F. with the air at 60° F., or preheating the air to 1300° F. with the blast-furnace gas at 60° F. The author presents some calculations of heat available under definite, assumed conditions, and the capital and operating costs involved.

The Heating of Open-Hearth Furnaces with Mixtures of Blast-Furnace and Coke-Oven Gases. M. Conte. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 384-388). The author discusses the choice of the mixture of gases, the control of the furnace, mixing the gases, and makes a comparison of the heating by means of gas mixtures with heating by producer-gas.

The By-Product Coke and Gas Industry. C. J. Ramsburg. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 84-85). The author discusses the increasing attention now being paid in America to the use of coke-oven gas outside the coke-oven plant and steelworks, and mentions the growing practice of the coke-oven plants of selling their surplus gas to gas-distributing companies. In this connection, he points out the advantages of substituting blast-furnace gas for coke-oven gas for heating coke-ovens; the latter gas has five times the heating value of the former gas, and its transportation over long distances can be profitable, whereas that of blast-furnace gas is not. The author gives a table of 12 new by-product plants put under construction or operation in 1928, together with the number of ovens and the annual coal carbonising capacity.

Gas Engines in the Iron and Steel Industry. T. B. Morley. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 302-304). The possibilities of the use of blast-furnace gas in gas engines, the design and performance of modern gas engines, and the cost of power production are discussed.

LIQUID FUEL.

The Hydrogenation and Liquefaction of Coal. D. G. Skinner and J. I. Graham. (Fuel in Science and Practice, 1928, Vol. 7, Dec., pp. 543-555). The influence of composition, pressure, temperature, and catalysts upon hydrogenation has been investigated.

Hydrogenation of Coal in Presence of Catalysts. B. Hlavica. (Brennstoff-Chemie, 1928, vol. 9, July 15, pp. 229-231). The author

describes investigations on the influence of various factors—particularly of catalysts—on the high-pressure hydrogenation of coal. He concludes that the yield and quality of tar are dependent not only on the catalysts, but also on the temperature, pressure, and duration of heating. He distinguishes three phases of hydrogenation: in the first phase, between 300° and 400° C., hydrogen is absorbed rapidly, and the coal is transformed into an asphaltic mass with the formation of water by the deoxidation of the coal; in the second phase, hydrogen is absorbed less rapidly, and the mass softens and liquefies; up to this point not much gas is evolved; during the third phase, the liquid coal decomposes violently, forming large quantities of gaseous and low boiling-point liquid hydrocarbons. The author discusses the catalysts which may be used and their action.

The Manufacture of Liquid Fuels and of Manures by Synthesis. C. Berthelot. (*Revue de l'Industrie Minérale*, 1928, No. 188, Oct. 15, pp. 410–426). The author commences by discussing the world output of coal in order to demonstrate the necessity for the application of new methods of treating the coal to face the present-day situation in which the output of coal is greater than the demand. He then compares the composition of various substances, and shows that coal is the most suitable raw material for the production of liquid fuels. He next discusses what liquid fuel should be produced, and the position of affairs as regards fertilisers. He then reviews the four general methods for the chemical utilisation of coal—namely, low-temperature carbonisation, high-temperature carbonisation, hydrogenation of coal or of primary tar, reduction of carbon monoxide by hydrogen in the presence of catalysts—and deals with matters relating to these processes, such as the provision of the hydrogen and of the motive power necessary for the synthetic operations. Finally, he deals with the question of the capital required for various processes, and touches on the most suitable centres in France and Germany for the production of liquid fuels and fertilisers.

A Few Remarks on the Synthesis of Liquid Fuels in Germany. Mathignon. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 328–329). An account of the Bergius process in operation at the Merseburg Works, near Halle.

The Nature and Properties of Fuel Oil. J. S. Schofield. (*Heat Treating and Forging*, 1929, Vol. 15, Mar., pp. 350–352).

Oil Furnaces are Economical. H. A. Hepburn. (*Heat Treating and Forging*, 1929, Vol. 15, Mar., pp. 359–361). An outline of heating furnace practice operating on fuel oil, and directions for handling and burning the oil, are given.

PRODUCTION OF IRON.

PIG IRON.

Blast-Furnace Development in 1928. H. A. Berg. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 67-68, 83). A brief review of developments in American blast-furnace design and practice during the past year.

Trend in Blast-Furnace Field. F. H. Willcox. (Iron Age, 1929, Vol. 123, Jan. 3, pp. 42-44). A review of developments in American blast-furnace practice during the past year.

Late Blast-Furnace Plant Developments. (Iron Age, 1929, Vol. 123, Feb. 21, p. 549). Recent developments in blast-furnace practice were discussed at a meeting of the Eastern States Blast-Furnace and Coke-Oven Association, Feb. 15, 1929. Discussion of the merits of the wide hearth furnace showed that furnaces with hearth diameters of 22 ft. are entirely satisfactory, whether viewed from the standpoint of the quality of the pig iron produced, smoothness of operation, or furnace economy. A new type of stove is being tried at the Mingo Works of the Carnegie Steel Co. The stove has a conical top, with a taper from the body diameter of 21 ft. to 8 ft., and includes the use of a burner in the top.

Blast-Furnace Plant at Hamilton. O. E. Clark. (Blast-Furnace and Steel Plant, 1929, Vol. 17, May, pp. 690-693). Illustrated particulars are given of the stove and gas-cleaning equipment at the blast-furnace plant of the Hamilton Coke and Iron Co., Ohio. The iron produced at these works is transported in special ladles to the steel furnaces of the American Rolling-Mill Co., a distance of over 10 miles. The stoves are four in number, one of which is of the old Kennedy type. The other three are of the Diehl type and are 20 ft. in diam., 92 ft. high, and have a heating surface of 65,225 sq. ft. each. The gases are led from the furnace top to a primary dust collector, where 40 per cent. of the heavy dust is drawn off. The gases are then led to a Vortex dry cleaner of the centrifugal type. After leaving the dry cleaner about 20 per cent. of the gas is wet washed and used in the stoves; the other 80 per cent. is led direct to the boilers.

New Australian Blast-Furnace Plant. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 266-269). **Australian Iron and Steel**

Ltd. (Iron and Coal Trades Review, 1929, Vol. 118, Jan. 11, pp. 35-38). **800-Ton Blast-Furnace of the Australian Iron and Steel Ltd.** H. von Escher. (Zeitschrift des Vereines deutscher Ingenieure, 1929, Vol. 73, Mar. 9, p. 329). Illustrated descriptions are given of the layout and equipment of the blast-furnace plant of Australian Iron and Steel Ltd., at Port Kembla.

Dovel Type Blast-Furnace put on Test. J. P. Dovel. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Dec., pp. 1555-1558; 1570). The Dovel type of blast-furnace was designed principally to prevent the production of flue-dust, and the results are given of a six-day test run on a burden of hard ore crushed to 1-in. size. The dimensions of the furnace are given, together with an illustration of the recuperator which preheats the cold blast before it enters the stoves. The tests show that with ore as ordinarily crushed and as re-crushed, this re-crushing increased the thermal efficiency about 16 per cent., and only increased the flue-dust from 24.6 lb. to 42.53 lb. per ton of iron.

Ward-Leonard Control as Applied to Blast-Furnace Skip Hoists. E. Anderson. (Iron and Steel Engineer, 1929, Vol. 6, Feb., pp. 65-71). Curves and data are presented showing the comparison in operation of a skip hoist driven by a squirrel cage induction motor and one driven by direct current motors controlled by the Ward-Leonard system.

MacKee Charging Apparatus of Modified Construction Erected at the Belorezk Charcoal Blast-Furnace, Ural. S. Koptevsky. (Journal of the Russian Metallurgical Society, 1928, No. 1, pp. 169-171). (In Russian.)

Progress in the Utilisation of Hot-Blast Apparatus. Communication from the Fuel Department of the Differdange Works. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928: Chaleur et Industrie, 1928, Vol. 9, Nov., pp. 390-393). The subject is dealt with under the following headings: General considerations; the heating of Cowper stoves in tandem; description and operation of the Differdange plant; results of practical tests; advantages of the system.

Modern Construction and Heating of Cowper Stoves. E. Pierre. (Revue Universelle des Mines, 1929, Series 8, Vol. 1, Jan. 15, pp. 43-49). The author reviews the improvements that have been made in the burners, the checker work, and the heat insulation of Cowper stoves. The progress achieved in the two first-named directions has been dependent upon the advances made in the cleaning of blast-furnace gas.

Utilises Chimney Gases to Heat Cold Blast. (Iron Trade Review, 1928, Vol. 83, Nov. 8, pp. 1184-1185). At the blast-furnaces of the

Sloss-Sheffield Iron and Steel Co., Birmingham, Alabama, the waste heat in the gas exhaust from the hot-blast stoves is employed for increasing the temperature of the blast before it enters the stoves. The recuperator consists of a chamber lined with heat-insulating material. The air is heated by passing it through a coil over which the exhaust gases are allowed to circulate. Originally the blast entered the stoves at about 180° F., but since the use of the recuperator its temperature has been increased to 450° F.

Fuel Economy on Blast-Furnace Plants. J. B. Fortune. (Fuel Economist, 1929, Vol. 4, Jan., pp. 197-200). The preheating of gas and air before combustion in hot-blast stoves is discussed, and an installation of recuperators at an American plant is described. The operation of stoves in tandem (coupled together) is also briefly discussed.

Turbo-Blowers for the Blast-Furnace. J. Guest. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 114-116). The author sets forth those features that have contributed to the successful performance of the turbine-driven centrifugal machine for supplying blast.

Device Plugs Tap Hole of Blast-Furnaces. C. Longenecker. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 122-123). **Plugs Iron Notch with the Blast on Furnace.** J. D. Knox. (Iron Trade Review, 1928, Vol. 83, Dec. 20, pp. 1555-1557, 1566). An electrically operated clay gun for closing tap holes is described and illustrated.

Pig Bed Dressing and Moulding Machine. (Iron and Steel Industry, 1928, Vol. 2, Dec., pp. 77-80). An illustrated account is given of a new type of pig bed moulding machine. The carriage on which the machine is mounted travels on two lattice trusses jointed together to form a bridge structure spanning the entire pig bed. The ends of the bridge rest on trucks travelling on rails along the side of the casting house. The machine consists essentially of the sand-dressing carriage and of the moulding machine proper. The latter comprises a moulding plate carrying the patterns and the pressure truck. The machine can be raised and lowered as required.

Ropeways in Blast-Furnace Practice. A. H. Wright. (Iron and Steel Industry, 1929, Vol. 2, May, pp. 235-236). The advantages of using aerial ropeways in blast-furnace plants are pointed out, and brief particulars are given of their use on the Continent.

Anti-Friction Bearings at Blast-Furnaces. S. R. Cox, jun. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 104-106). The use of roller-bearings on auxiliary equipment for blast-furnaces is discussed.

First Report on Blast-Furnace Plant and Practice. (Presented to the Iron and Steel Institute, May 1929: this Journal, p. 47).

Blast-Furnace Research. W. Lennings. (Iron and Coal Trades Review, 1928, Vol. 117, Nov. 26, p. 729). An abridged translation of a report of the Blast-Furnace Committee of the German Ironmasters' Association. The full report is published in the Archiv für das Eisenhüttenwesen, 1928, Vol. 1, Mar., pp. 549-564. (See Journ. I. and S.I., 1928, No. I. p. 774.)

A Review of Blast-Furnace Research. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Mar., pp. 425-430, 435). A translation of a report by G. Bulle. The report gives the results of an investigation of the influence of the character of ore and coke on blast-furnace operation. The major portion of the report deals with the reactions inside the blast-furnace. (See Journ. I. and S.I., 1928, No. I. p. 773.)

Progress in German Blast-Furnace Practice. H. A. Wagner. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 81-83). The outstanding features of German blast-furnace practice are discussed and compared with American practice.

The Blast-Furnace and its Economic Position. H. E. Wright. (Paper read before the Cleveland Institution of Engineers, Apr. 8, 1929: Iron and Coal Trades Review, 1929, Vol. 118, Apr. 12, pp. 527-528). The author deals with the economic position of the blast-furnace, pointing out the importance of correct design, and discusses the possibilities of using a competitive process for the reduction of iron. The alternatives suggested from time to time have comprised processes: (1) For reduction of ore by gases with subsequent treatment of the metallic sponge or dust. No process can supply the gases or treat the sponge better than the blast-furnace does. (2) Reduction of ore direct by carbon or fuel. This, although not the most economic method of blast-furnace reduction, can in the normal case be equally well performed by the blast-furnace. (3) Direct reduction by a fuel flame with subsequent combustion of the gases to preheat the ore. This introduces the sulphur trouble unless the ore and fuel are pure; moreover, the short time of possible contact also renders reduction in this way a very critical and speculative problem. (4) Electrical reduction, or electrical fusion, combined with one or other of the previously mentioned processes. For such electrical reduction, electricity has usually to be generated by means of fuel, and as, on reconversion to heat, only a small percentage of the original heat is realised, the blast-furnace appears to be better able to provide the required heat economically from direct fuel. The author maintains that the blast-furnace is a proved and successful apparatus for the production of iron or steel in the large bulk demanded by commerce, in places convenient both to the markets and the sources of ore and fuel. Although it involves more capital cost to accomplish the result, there is no reason why its overall fuel efficiency cannot be brought to

80 per cent. or more, and it is probable that no practical alternative exists for which so good a case can be made out.

The Blast-Furnace Theory. R. Franchot. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 170). The subject is discussed under the following headings: Science of blast-furnace metallurgy, fuel economy related to reduction equilibrium, influence of theories of Bell and Johnson, reduction of Fe_2O_3 by CO, heat relations involved in ore reduction, and relation of solution loss to fuel energy. Tables are included showing a comparison of smelting Cleveland ore and Mesabi ore. Operating data are given, and from them are calculated the significant relations on the basis of a pound of coke carbon charged into the furnace. The comparison shows the failure of the reduction equilibrium theory to explain high coke ratios or low smelting efficiency. The comparative heat balances illustrate the working of thermodynamic principles which Johnson was the first to apply. The author suggests that the endothermic chemical reactivity of the air nitrogen, as evidenced in various ways, gives a basis of fact upon which to account for a substantial part of the hearth heat as developed by the oxygen. The hypothesis that heat development by air combustion in the hearth is restricted by nitrogen fixation, that the availability of the combustion heat for high-temperature work is seriously limited by this action, that consequently the hearth work requires a larger amount of the coke than would otherwise be the case, has a strong basis of fact and affords a reasonable explanation of the furnace behaviour. The manifest inadequacy of generally held theories may perhaps give the nitrogen hypothesis an added value.

Briefly stated, the idea is that as the blast heat is increased and the combustion temperature tends to rise, this effect is increasingly offset by increasing nitrogen activity, the difficulty of raising the hearth temperature being increased by a resistance associated with the combustion itself. In other words, the effectiveness of the high blast heats now in common use is in substantial measure curtailed by an endothermic formation of nitrogen compounds in the combustion zone. Certain facts which the author believes support the hypothesis are recapitulated, and objections to the nitrogen hypothesis are discussed.

Criticism on the Paper of M. Derclaye on "Modern Scientific Principles in the Working of Blast-Furnaces of Large Output." J. Seigle. (Revue de Métallurgie, Mémoires, 1929, Vol. 26, Jan., pp. 12-18). In discussing the work of Derclaye (*see* Journ. I. and S.I., 1928, No. II. p. 301) the author deals with the following three points: expressions relating to heat exchanges in the zone of combustion; data for calculating the height of the zone of combustion, and the impossibility of making this calculation; the ideal working index of Gruner and the true ideal working index of Richards.

An Estimate of the Material and Heat Balances of the Blast-Furnace, Based on the Top Gas Analysis and the Air Volume. H. Bansen. (*Revue de Métallurgie, Mémoires*, 1928, Vol. 25, Nov., pp. 614-629). A French translation of the original German paper (*see Journ. I. and S.I.*, 1927, No. II. p. 518).

Quality of Pig Iron and Castings as Affected by Blast-Furnace Practice. A. L. Boegehold. (Paper read before the American Foundrymen's Association, Apr. 1929). The author describes an investigation carried out to determine the relation between the properties of cast iron and the conditions of blast-furnace operation during the manufacture of the pig iron. Pig irons of known history were obtained in approximately 75-ton lots and studied by converting into cast iron and investigating the various properties. Data are presented of blast-furnace operation, and the factors responsible for variations in working are discussed. The results demonstrate that the physical characteristics of pig irons persist during remelting in the cupola and greatly influence the physical properties of the cast iron. The properties of cast iron which are dependent upon the amount of combined carbon present and upon the ease with which combined carbon is retained by rapid cooling are related directly to the amount of moisture in the blast. The machinability of cast iron increases and the tendency for the formation of white iron diminishes as the moisture content of the blast is reduced. The tendency for the formation of shrinkage cavities is decreased by increasing the rate at which the ore burden travels through the blast-furnace, and this rate depends upon the burning rate of the coke used. The quality of the coke used at the blast-furnace affects the pig iron in several ways, making it extremely important to have accurate control of this material. An appendix to the paper contains a description of a combustibility test for coke developed by the author.

Blast-Furnace Metal for Castings. D. Baker. (*Iron Age*, 1928, Vol. 122, Dec. 13, pp. 1501-1502). A discussion of the conditions and costs involved in the use of direct metal in pipe foundries. According to the author, castings can be made satisfactorily from blast-furnace metal.

Scrap in the Blast-Furnace. J. B. Fortune. (*Fuel Economist*, 1929, Vol. 4, Feb., pp. 247-249). The author discusses the effect of scrap in the blast-furnace. The results obtained with the use of scrap in American blast-furnaces are presented.

Twenty Months' Results of Dry-Blast Operation. E. H. Lewis. (Paper read before the Iron and Steel Institute, May 1929 : this Journal, p. 79).

Some Notes on the Loss of Pressure and Temperature in Cold-Blast Lines. J. S. Fulton. (Proceedings of the Engineers' Society of Western Pennsylvania, 1928, Vol. 44, June, pp. 159-172). It has been claimed that, roughly, 5 per cent. of the gas for the stoves could be saved at 20 lb. blast pressure and 1000° F. hot-blast temperature by delivering the air into the cold-blast main at 250° F. instead of 200° F., with, of course, the same intake temperature. In order to determine the probability of this saving, the author has obtained readings from a number of plants, and from the figures given in the paper he concludes that there is a very slight indication that the greater the mean temperature difference, the greater the B.th.u. loss per sq. ft. per hr. However, there is no conclusive set of figures to prove or disprove this.

Some Recent Blast-Furnace Explosions. A. Wagner. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 293-296; Mar., pp. 436-438). A translation of a report on blast-furnace explosions which occurred at two works in Germany. (See Journ. I. and S.I., 1928, No. II. p. 301.)

Production of High Alumina Slags in the Blast-Furnace. T. L. Joseph, S. P. Kinney, and C. E. Wood. (United States Bureau of Mines, 1928, Technical Paper No. 425: see Journ. I. and S.I., 1928, No. I. p. 778).

Effect of Barium Oxide on the Desulphurising Power of Blast-Furnace Slags. C. E. Wood and T. L. Joseph. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 181). This paper is a report of experimental work undertaken to determine whether barium oxide in any quantity increases the desulphurising action of blast-furnace slags. The experimental procedure and apparatus used are described. To determine the relative proportions of sulphur absorbed by the slag while in contact with a bath of molten metal, under comparable conditions of temperature and composition, also when fine streams of metal were poured through a column of slag, two types of experiments, designated "bath" and "dropping" tests, were carried out. A combination of these tests was also performed. The results are set forth in detail. The effect of viscosity on desulphurisation in the blast-furnace is also touched upon. The experimental data obtained, although incomplete, indicate that:

The addition of sufficient quantities of barium hydrate to slag of normal composition to introduce up to 5 per cent. BaO into the slag does not markedly increase the desulphurising action of the slag. Such an addition of BaO produced a small increase in the molar basicity of the slag and in its desulphurising action.

The desulphurising action of blast-furnace slag varies directly

with its molar basicity. A replacement of SiO_2 by BaO increases the molar basicity of the slag and its desulphurising action. The industrial furnace slag referred to in the report has a slightly higher molar ratio of bases to acids than any of the slags used by the writers. Such slag would have more desulphurising power than normal slag, due primarily to its higher molar ratio and not to the BaO .

The desulphurising action of a slag is more closely related to the molar ratio of bases to acids than to basicity based upon percentages of bases and acids present, particularly when a substance of high molecular weight like BaO is involved.

Desulphurisation of metal by contiguous layers of slag was almost directly proportional to time of contact over a period of 60 min.

Surface contact between slag and metal has an important bearing upon desulphurisation, as shown by the amount of sulphur removed when globules of iron were passed through a layer of slag. Under similar conditions of temperature, quantities of metal and slag, and concentrations of sulphur from 60 to 80 per cent., as much sulphur was removed in less than 5 min. when globules of iron were passed through a layer of slag as was removed during 60 min. contact between quiescent layers of slag and metal.

Barium oxide is about one-third as effective as an equal weight of CaO in removing sulphur and in fluxing SiO_2 and Al_2O_3 . It was not determined whether the molar basicity of blast-furnace slag can be increased by the addition of BaO to such an extent as to have an appreciable effect upon the rate of desulphurisation without producing a slag that is too viscous from other angles of practice.

Long-Time Tests on Concrete with Various Additions, particularly Blast-Furnace Lump Slag. A. Guttman. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Jan., pp. 401-403). The article is a report on the development of the use of blast-furnace slag in the United States, and on comparative tests on the crushing strength of slag concrete and natural stones. In 1927 some 10,000,000 tons of blast-furnace slag were utilised in the U.S. Of this quantity 45 per cent. was used for road-making, 25 per cent. for concrete, 25 per cent. as railway ballast, and the remaining 5 per cent. for other purposes, mainly slag sand for Portland cement. In the last 20 years about 15,000,000 cu. m. of slag concrete has been used in building and no case of failure has yet been recorded. The composition of the slags from 10 different furnaces in Ohio and Pennsylvania is recorded, and shows little variation, the ferric oxide being 0.50 to 2.0, silica 32 to 36, alumina 12 to 14, lime 32 to 42, sulphur as CaS 0.9 to 1.29, sulphur as CaSO_4 0.20 to 0.50 per cent. Test specimens of concrete made from these slags were stored under wet sand for 35 days; they were then removed to the dry storeroom of a laboratory and stored 5 years, and finally brought into the open. Diagrams show the results of crushing tests on slag concrete after storage for 180 days, after 5 years' storage in a dry place, and

after 5 more years in the open. The strength rises for the first two or three years in the dry and then falls to about the original strength or below, but after removal into the open it again rises steadily to about double the original strength.

Utilisation of Blast-Furnace Slag for Cement. W. Kosfeld. (Stahl und Eisen, 1929, Vol. 49, Feb. 21, pp. 243-249). The author discusses the properties and chemical composition of those blast-furnace slags which are most suitable for cement manufacture. Acid slags alone come into consideration. The conditions for specifications for slag cement are outlined, and results of slag cement tests are given.

Use and Properties of Slag Wool. A. Guttmann. (Stahl und Eisen, 1929, Vol. 49, Jan. 24, pp. 97-101). The value of slag wool as a heat insulation and fireproof material and as a deadener of sound is so great that it is remarkable that the material does not find a wider application than as a lagging for steam pipes, boilers, and refrigerators. It is also used as a filtering medium in gas-cleaning plants. It commands a higher price than any other product from slag. The most suitable kinds of blast-furnace slag for the manufacture of slag wool are the thin fluid, that is siliceous, slags low in sulphur. The criterion of a good slag wool is the fineness of the thread, which should not average more than 3.5 to 3.8 μ in thickness; the weight of such a material is about 1 kg. per 10,000 cu. cm. (10 litres), and its porosity is about 93 per cent. Data concerning its low heat-conducting properties, composition, and refractoriness are given in tabular form.

Suitability of Blast-Furnace Slag as Manure. C. Weise. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 283-286). In the United States the limey slags from blast-furnaces running on basic pig have for over 10 years been extensively used on farm lands on account of their high manurial value for soils that have become sour from the use of other artificial manures which when exhausted leave an acid residue in the ground. Experiments have shown that slags with a high content of lime and a small quantity of magnesia present in the form of silicates have a greater value as a manure than ordinary quicklime. The results of comparative trials in America with lime and slag are shown diagrammatically, and the extension of the use of such slags in Germany is recommended.

Production of Iron and Steel in the Electric Furnace. A. Stansfield. (Fuels and Furnaces, 1929, Vol. 7, Jan., pp. 87-95; Feb., pp. 251-260, 282). In the first article the author discusses the electric smelting of iron ore in the Swedish electric furnace and various methods for the direct reduction of iron ore. The second article contains a discussion of the developments in design, construction, and operating features of the more important types of electric steel-melting furnaces.

WROUGHT IRON.

Essentials of Hand-Puddling Unchanged in Century. G. A. Richardson. (Iron Trade Review, 1929, Vol. 84, Jan. 31, pp. 317-320, 330).

Wrought Iron and the Puddling Process. G. A. Richardson. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Dec., pp. 1566-1570). A description is given of the manufacture of wrought iron, as carried out at the plant of the Bethlehem Steel Co., by the hand-puddling process.

Makes 4000 Tons of Iron Monthly by Synthetic Process. J. D. Knox. (Iron Trade Review, 1929, Vol. 84, Feb. 7, pp. 382-384). **Wrought Iron Made by a New Process.** C. Longenecker. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 263-265). An outline is given of the Aston process for the production of wrought iron. Pig iron is melted in a cupola and subsequently refined in a Bessemer converter. The blown metal is poured slowly into a slag in the bottom of a cast-iron container called a shotting cup, where "it comes to nature." No rabbling or stirring is necessary, and it is stated that the spongy mass of iron is identical in appearance with hand-puddled balls. The slag used is produced in an open-hearth furnace. The materials employed include roll scale, cinder, and sand. The spongy material is removed from the container and pressed into blooms and rolled into muck bar and billets. An experimental plant is in operation at Warren, Ohio, by the A. M. Byers Co., where 4000 tons of muck bar and billets are produced per month by this process.

DIRECT PROCESSES.

Direct Iron Production. (Fuel Economist, 1928, Vol. 4, Nov., pp. 111-112; Iron and Steel Industry, 1928, Vol. 2, Dec., p. 81). Brief particulars are given of the Duffield process for the production of sponge iron. A mixture of ore and low-grade slack is charged into a vertical retort, the walls of which are surrounded by a heating chamber in which the gases from the reduction process are burned. The retort is continuously fed from the bottom by a hydraulic ram, and the product after reduction is discharged at the top into cooling chambers through chutes. The gases generated rise in the retort into more highly heated zones, and the ordinary $\text{CO}_2 + \text{C} = 2\text{CO}$ reaction then occurs, the CO immediately attacking iron oxide $\text{Fe}_x\text{O}_{y+1} + \text{CO} = \text{Fe}_x\text{O}_y + \text{CO}_2$. The reactions occur rapidly and repeatedly so long as unreduced Fe_xO_y and C are present in the charge. The exit gases from the top of the retort are carried to a gas main and burned in the combustion chamber surrounding the retorts. The product is cooled to under 300°C ., and after being passed through a disintegrator is

magnetically separated, the metallic portion having an iron content of up to 96 per cent. The special feature of the retort operation is the travel of solids and gases in the same direction, in intimate contact, and through zones of gradually increasing temperatures, beginning at 700° C. and ending at 1000° C., or thereabouts. At no stage of the operation is the temperature sufficiently high to cause incipient fusion or any viscosity in the charge, and the phenomenon of reduction breaks down the intimate physical contact of iron and unaffected gangue, so that the product of low-grade ore treatment, which is pulverulent, may be magnetically treated, though this will not be necessary in the case of rich ores.

Sponge Iron by the Smith Process. G. B. Waterhouse. (Iron Age, 1929, Vol. 123, Apr. 25, pp. 1143-1145). An illustrated account is given of the Smith process for the production of sponge iron. The process is carried out in vertical ovens or retorts, similar to coke-ovens in design. The crushed ore or iron oxide material is mixed with carbonaceous material and charged into the oven, where it is heated and cooled by means of horizontal flues. It is preheated in the upper part of the oven by the waste gases, which leave the stack at about 400° F. The charge then enters the reduction zone, where temperatures range from about 1600° to 2000° F., and is subsequently cooled by the incoming air for combustion in the heating flues, being discharged at less than 250° F.

ELECTROLYTIC IRON.

The Production of Heavy Metals by Electrolysis while Melted.
II.—Production of Iron, Chromium, and Manganese from their Oxides and Silicates. G. Neuendorff and F. Sauerwald. (Zeitschrift für Elektrochemie, 1928, Vol. 10, Apr., pp. 199-204). The authors have continued their researches on the electrolysis of iron, and have obtained very high efficiencies. They have shown that it is necessary to electrolyse in a suitable furnace at high temperatures in order to get good current efficiency; the latter varies also with the duration of electrolysis. According to the conditions employed, iron without carbon, steel, or cast iron may be obtained. In the course of fusion, the iron silicates employed underwent a thermal dissociation with loss of oxygen. The electrolysis of chromite was also carried out with a good current efficiency; the product was a carburised iron-chromium alloy. With regard to manganese, starting with a manganese ore diluted with an iron ore, the product was an alloy containing only a very little manganese.

Alkaline Electrolytic Iron. S. J. Lloyd. (Paper read before the American Electrochemical Society, May 1929). In 1917-18 Estelle

suggested and patented the electrolytic deposition of metallic iron from a suspension of its hydroxide in strong hot caustic soda. His results are confirmed, and extended in the present paper to various ores of iron, and a study is made of the regeneration of the caustic solution by means of lime.

Sulphur in Electrolytic Iron and its Removal. K. Oma. (Bulletin of the Institute of Physical and Chemical Research, Tokyo, 1929, Vol. 8, Feb., pp. 126-130). (In Japanese.) Sulphur contained in electrolytic iron, deposited from the sulphate bath with ferrous ammonium sulphate solution used as an electrolyte, can exist in two forms, as sulphate derived from the electrolyte, and as sulphide from the anode. When treated at high temperatures, annealed or fused, most of the sulphate is reduced to iron sulphide and some to hydrogen sulphide. The desulphurisation of electrolytic iron is accomplished by heating it in hydrogen above 800° C. The rate of desulphurisation is a function of time, temperature, and the grain-size of the iron to be treated.

IRON INDUSTRIES.

The Position and Prospects of the Steel Industry. W. R. Scott. (Journal of the West of Scotland Iron and Steel Institute, Session 1928-1929, Vol. 36, pp. 36-45).

South African Iron and Steel Industry. H. J. Van Der Byl. (Journal of the Royal Society of Arts, 1929, Vol. 77, Mar. 29, pp. 500-512; Iron and Coal Trades Review, 1929, Vol. 118, Mar. 1, p. 329; Mar. 8, pp. 356-357). A review of the history and development of the iron and steel industry in South Africa.

Report on Economic Conditions in France in 1928. J. R. Cahill. (Department of Overseas Trade, London, 1928; H.M. Stationery Office). The rapid development of the French tinplate industry is shown. Prior to the war the bulk of French tinplate was produced in five works; now in 1928 the number of mills is about 70, but these are all under the control of a few concerns, and the bulk of the output is controlled by a single group. About one-half of the total output is produced by the firm J. J. Carnaud et Forges de Basse-Indre, which owns some 14 or 15 mills. The annual output capacity of the French industry is at present 75,000 tons.

The Supply of Raw Materials for the German Iron Industry. H. Niebuhr. (Stahl und Eisen, 1928, Vol. 48, Nov. 29, pp. 1672-1674). A report has been published by a Committee appointed to inquire into

the sources and security of the supply of raw materials for the German iron and steel manufacturing industry, and it deals mainly with the questions of the supply of ore and scrap, as the two most important of such materials. A comparatively small proportion of domestic ores is now used, the imported ores amounting to four-fifths of the total requirements, whereas before 1914, 61.3 per cent. of the ores used were from domestic sources. The amount of scrap charged to the blast-furnaces in Germany has diminished year by year since the war. The proportion of scrap used in blast-furnaces in 1926 was 6.75 tons per 100 tons of pig iron produced. In 1926 the total amount of scrap used in the industry was 6,006,000 tons. The industry is almost independent of outside supplies of scrap, and of the above total used in 1926, 5,974,000 tons were of domestic origin. With regard to the ore supplies, Scandinavia is the chief source, while a large amount is also imported from Lorraine, Northern France, and Spain. The supplies are considered to be assured for a long time ahead, by means of long-term contracts and agreements.

The Johannes Works at Duisburg. (Kruppsche Monatshefte, 1929, Vol. 10, Jan.-Feb., pp. 18-19). A brief historical note on the Krupp blast-furnace works at Duisburg. Founded in 1856, the works were purchased by Krupp in 1872 in order to supply his steel foundries with the necessary raw material, which had previously been bought in the open market.

The Witkowitz Ironworks, 1828-1928. (Montanistische Rundschau, 1928, Vol. 20, Dec. 1, pp. 677-680). The article describes the growth and development of the Witkowitz Ironworks. About the year 1825 Professor F. X. Ripl, of the Vienna Polytechnikum, recognised that the best means for developing the mineral wealth of the district round about Vienna was by the building of a railway, and, in order that the plant and materials for this project should be produced in the locality, he took active steps to inaugurate the Rudolfs-Hütte Ironworks, which was the foundation upon which the present-day Witkowitz Works have been built up.

Spain as an Iron-Producing Country. W. Harnickell. (Stahl und Eisen, 1929, Vol. 49, Apr. 18, pp. 536-539). A short note on the Spanish iron industry is given, with information concerning the mineral resources and mineral trade, the latest developments in iron and steel production, and iron trade statistics. The ore resources are enormous, and if the coke supply can be cheapened there is a prospect of extensive development of the industry.

Spain Builds Flourishing Industry on own Mineral Resources. V. Delport. (Iron Trade Review, 1928, Vol. 83, Oct. 11, pp. 918-920). A brief sketch is given of the Spanish iron and steel industry.

Considerable New Capacity in 1928. (Iron Age, 1929, Vol. 123, Jan. 3, pp. 83-88). Particulars are given of the additions made to the blast-furnace and open-hearth furnace capacity in the United States during the past year.

The Anshan Iron and Steel Works in Manchuria. (Iron and Coal Trades Review, 1929, Vol. 118, Apr. 26, p. 610). The existing plant at this works consists of two 300-ton blast-furnaces erected during the war. Arrangements are in progress for the erection of a 500-ton furnace and for increasing the capacity of the old furnaces to 350 tons, giving a combined producing capacity of 360,000 tons per year. The erection of a new steel mill with a capacity of 240,000 tons per year is contemplated. The new steel plant will include five 60-ton open-hearth furnaces, billet and slab mills, rod mill, tinplate mill, black sheet house, roll house, firebrick plant, and power house.

The Iron Industry of Masenderan (North Persia). E. Böhne. (Stahl und Eisen, 1928, Vol. 48, Nov. 8, pp. 1577-1580). Some notes are given on the geology of Masenderan, the mountainous district bordering the southern end of the Caspian Sea, and separating it from the bare central plateau of Persia. In the valleys are deposits of excellent coking coal, the seams varying from 3 to 7 ft. in thickness, and lenticular masses of clayband ironstone likewise occur. A very primitive iron industry has existed here for some thousands of years, and is still carried on in the same manner, no doubt, as in ancient times. The coal has never been developed, and the fuel used is charcoal derived from the extensive forests filling the valleys. Illustrations of the small smelting furnaces and charcoal heaps are given.

HISTORICAL.

Presidential Address. H. Louis. (Presented to the Iron and Steel Institute, May 1929: this Journal, p. 29). The early history of iron manufacture is reviewed.

History of Iron Founding in the Midlands. D. H. Wood. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Apr. 11, pp. 269-272). A review of the parts played by Dudley, Yarranton, Blewstone, Darby, Wilkinson, and others in the development of the iron industry in the Midlands.

Sidelights on the History of the Iron Smelting Furnaces of Styria. R. Schaur. (Stahl und Eisen, 1929, Vol. 49, Apr. 11, pp. 489-498). An historical account of the development of the blast-furnaces in Styria from the bloomery hearths of pre-Roman times down to the present day.

FOUNDRY PRACTICE.

GENERAL FOUNDRY PRACTICE.

Some Recent Developments in Cupola Design. F. K. Neath. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, May 16, p. 368). Hot-blast cupolas, use of pulverised fuel firing, injection of water into the combustion zone, blast control, and thermocouple measurements are briefly discussed.

The Cupola with Water Injection and the Schürmann Furnace in Continuous Operation. G. Ott. (Die Giesserei, 1929, Vol. 16, Feb. 1, pp. 111-113). Comparative tests on a cupola with and without water injection show the favourable influence of the addition of water. Brief notes on the Schürmann furnace are also given.

The Poumay Cupola. J. Cameron. (Paper read before the Institute of British Foundrymen, Feb. 29, 1929: Foundry Trade Journal, 1929, Vol. 40, Mar. 21, pp. 215-216). The Poumay system of cupola melting is described, and tables are included showing the coke consumption in an ordinary cupola and in one of the Poumay type, analyses of the gas, tapping temperatures, analyses of the metal produced, and tapping rates.

The Calculation of the Useful Height of a Foundry Cupola. M. Karnaoukhov. (Iron and Steel Industry, 1928, Vol. 2, Dec., pp. 83-85). Theoretical considerations involved in cupola design, and particularly the calculation of the useful height, are dealt with mathematically.

An Analysis of the Performance of 54-in. Cupolas, Based upon Records of Practical Operation. E. E. Marbaker. (Paper read before the American Foundrymen's Association, Apr. 1929). In order to determine the conditions surrounding the practical operation of 54-in. cupolas a questionnaire was sent to a number of foundries, and the information collected is presented by the author. Tables show in detail the operating conditions of eight straight-lined and eight boshed cupolas for the melting of grey iron. The results are discussed under the following headings: Effect of boshed linings on the melting rate, temperature of the molten iron, coke consumption, thermal efficiency,

air supply, theoretical calculation of coke and air, and the value of a second row of tuyeres.

A Study of the 36-in. Cupola. F. B. Coyle. (Paper read before the American Foundrymen's Association, Apr. 1929). The author presents the results of an investigation in which an attempt was made by close control of cupola operation to improve the uniformity and quality of iron for the construction of Diesel engine parts for submarine service. Particulars are given of a number of heats, and various operating features are discussed. It was found possible to improve the tensile strength of the iron produced by nearly 30 per cent. and maintain the Brinell hardness between 200 and 220.

Melting Iron in the Cupola. J. E. Hurst. (Foundry, 1928, Vol. 56, Nov. 1, pp. 886-888; Nov. 15, pp. 928-930; Dec. 1, pp. 972-975; Dec. 15, pp. 1013-1016; 1929, Vol. 57, Jan. 1, pp. 29-32, 44; Jan. 15, pp. 63-64, Feb. 1, pp. 109-112; Feb. 15, pp. 164-167; Mar. 1, pp. 196-198; Mar. 15, pp. 234-237, 258; Apr. 1, pp. 298-301; Apr. 15, pp. 326-329; May 1, pp. 398-400, 405). The continuation of a long series of articles discussing in detail cupola practice. (See Journ. I. and S.I., 1928, No. II. p. 307.)

Melting Practice in the Foundry. H. M. Lane. (Paper read before the National Founders' Association, Nov. 22, 1928: Iron and Steel of Canada, 1929, Vol. 12, Jan., pp. 13-16).

Melting Plant and Appliances in Modern Iron Foundries. J. McLachlan and C. A. Otto. (Iron and Steel Industry, 1928, Vol. 2, Dec., pp. 91-94; 1929, Vol. 2, Jan., pp. 121-123; Mar., pp. 179-181). The continuation of a series of articles (see Journ. I. and S.I., 1928, No. II. p. 307). Charging platforms and hoists, pyrometers, and the handling of pig iron and scrap are dealt with.

Contribution to the Question of the Variation of the Carbon during Melting in the Cupola. H. Pinsl. (Die Giesserei, 1928, Vol. 15, Dec. 28, pp. 1292-1301). The author discusses the factors which control the carbon content of cupola-melted metal—namely, the chemical composition of the charge, the temperature of the melted product, the duration of contact of the iron with the coke, the solubility and solution velocity of the carbon, and the general manner of operation (blast pressure and volume, additional coke, size of iron pieces charged, &c.). Experiments made on cupolas with and without fore-hearths to control the carbon content are described.

The Change of the Total Carbon of Cast Iron During Melting. (Foundry Trade Journal, 1929, Vol. 40, May 2, pp. 327-328). An abridged English translation of the above paper by H. Pinsl.

Measurements on the Foundry Shaft Furnace. A. Achenbach. (*Die Giesserei*, 1929, Vol. 16, Apr. 5, pp. 309-318). The author quotes examples from practice of the mistakes and troubles that occur in the operation of the furnace, and stresses the importance of maintaining a thorough control of all the factors. He then illustrates, describes, and explains the method of using various measuring instruments for determining gas pressures, gas volumes, temperatures, &c.

Calculation of the Loss of Iron from the Cupola Slag. E. Knoppick. (*Die Giesserei*, 1929, Vol. 16, Apr. 5, pp. 321-323). By means of two examples it is shown that it is not correct to estimate the loss of iron by the iron content of the slag alone, but that other factors must be taken into account also.

The Carburisation of Steel Scrap in the Cupola. M. Miklau. (*Die Giesserei*, 1929, Vol. 16, Feb. 22, pp. 182-183).

The Use of Scrap in Grey Iron, Malleable, and Electric Steel Mixtures. E. K. Smith and F. B. Riggan. (Paper read before the American Foundrymen's Association, Apr. 1929). The authors discuss the requirements of scrap for use in foundry practice, and give typical mixtures for grey iron, malleable iron, and electric steel. The effect of varying percentages of scrap, and the effect of borings, tin, zinc, and burned material are shown. The desulphurisation of cast iron in relation to the use of scrap is also briefly discussed.

Fuel Economy in the Cupola. N. D. Ridsdale. (Paper read before the Institute of British Foundrymen: *Foundry Trade Journal*, 1929, Vol. 40, Feb. 28, p. 157). The following essential points which contribute to fuel economy in the cupola are discussed briefly: quality of cokes; thickness of layers of fusion coke; regularity of charging; volume of blast; and size of tuyeres.

Improvement of Cast Iron. L. J. Gouttier. (*Fonderie Moderne*, 1928, Vol. 22, Nov. 10, pp. 427-433). A description is given of the Walter process for the desulphurisation of cast iron.

The Use of Chill Tests on Electric Grey-Iron Melts for the Rapid Determination of the Probable Structure. K. F. Krau. (*Giesserei Zeitung*, 1928, Vol. 25, Dec. 15, pp. 707-709). The author points out the difficulty of attaining in castings just the desired composition, particularly when the silicon contents of the raw materials are subject to variation. He reviews methods of making tests to control this, and describes a rapid method which has been evolved specially for electric furnace operation. Test-bars about 12 to 25 mm. in diam. and 150 mm. long, the diameters corresponding to the wall thicknesses of the casting, are cast upright in sand with a normal moisture content

(about 7 per cent.). The degree of graphitisation of the bars is examined. The cast is then so arranged that the thinnest bar shows practically no graphite, the intermediate bar is mottled, and the thickest bar shows the normal cast structure.

Study on the Use of a Hardening Test for Cast Iron with Medium Silicon Content. M. Dudouet. (Transactions of the American Foundrymen's Association, 1928, Vol. 36, pp. 563-584). The results are given of an investigation of the preparation and use of small test-pieces, by means of which the total carbon + silicon content of ladle samples of cast iron can be determined from the depth of chill in the test-piece. The factors influencing the depth of chill in the pouring of the test-pieces are dealt with.

The Measurement of Cupola Air-Blast. (Foundry Trade Journal, 1928, Vol. 39, Dec. 20, pp. 451-452; 1929, Vol. 40, Feb. 14, p. 121). The continuation of an article describing various types of instruments for the measurement of air-blast.

Air Control in Foundry Operation. H. V. Crawford. (Paper read before the National Founders' Association, Nov. 1928: Iron Age, 1929, Vol. 123, Jan. 10, pp. 140-142). The author describes an automatic blast gate control for cupolas, which ensures the blower delivering a constant weight of air to the cupola under all conditions.

Theoretical Considerations on the Question of the Preheating of the Blast for Cupolas. E. Piwowarsky and R. Vogel. (Die Giesserei, 1929, Vol. 16, Feb. 15, pp. 147-153). The authors review the work of other investigators in their search for a measure of the combustibility of fuels. Experimental results of an investigation into the constants for the speed of reaction of oxygen and carbon at low gas current velocities are recorded, and from these it is deduced that the reactions are often dissimilar; accordingly the carbon reaction cannot be used alone as a measure of the combustibility of fuels. The authors conclude by discussing the conditions with higher velocities of the gas current and their bearing on cupola operation.

Hot-Blast Cupola in Pullman Foundry. R. A. Fiske. (Iron Age, 1929, Vol. 123, Mar. 28, pp. 872-875). A description is given of the hot-blast cupolas in operation at the plant of the Pullman Car and Manufacturing Corp., Michigan City, Indiana, together with the results of operating tests.

Operation of Cupola with Hot-Blast Increases Operating Economy. F. K. Vial. (Paper read before the American Society of Mechanical Engineers, Nov. 1928: Fuels and Furnaces, 1928, Vol. 6, Dec., pp. 1667-1670, 1690). The author presents the results obtained

with the use of hot-blast in cupolas and shows the savings which can be effected.

The Charging of the Cupola. L. Schmid. (Die Giesserei, 1929, Vol. 16, Apr. 12, pp. 335-353). The transportation of materials to the cupola, their storage, and charging them into the cupola are discussed from the economic point of view, namely, the cost of the liquid iron. The advantages and disadvantages of various methods of charging are considered.

The Influence of Inclined Charging of the Cupola on the Melting Process. E. Knoppick. (Giesserei Zeitung, 1929, Vol. 26, Feb. 15, pp. 109-110). By a systematic investigation the author has shown that from the metallurgical point of view mechanical charging has disadvantages in comparison with simple hand-charging.

A Novel Method of Cupola Charging. R. J. H. Ritchie. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Feb. 28, pp. 159-160).

Charging Cupolas Mechanically. J. A. Murphy. (Foundry, 1928, Vol. 56, Dec. 15, pp. 1023-1024). Various types of equipment used for the charging of cupolas are described.

Time Studies and Analysis of Operations in Works. V. Polak. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Jan., pp. 457-460). The effect of timing certain foundry operations and the consequent improvement in output and saving in labour are discussed.

Principles of Continuous Production. K. Oesterreicher. (Die Giesserei, 1928, Vol. 15, Nov. 9, pp. 1134-1137). The organisation of continuous production in a foundry and the layout of the plant for serial operation are discussed. The cooling and cleaning of castings is also touched upon. (See also Journ. I. and S.I., 1928, No. II. p. 310.)

Mass Production in the Foundry. K. Brieger. (Die Giesserei, 1929, Vol. 16, Apr. 19, pp. 375-380).

Synthetic Cast Iron from the Electric Furnace. (Giesserei Zeitung, 1929, Vol. 26, Mar. 15, pp. 161-168). This article, in German, is based on U.S. Bureau of Mines, Technical Paper No. 418, 1928 (see Journ. I. and S.I., 1928, No. I. p. 791).

High-Test Cast Iron. R. P. Lemoine. (Paper read before the American Foundrymen's Association, Apr. 1929). The author deals with the actual state of the production of high-duty cast iron in Europe, with special reference to French practice. In the first part of the

paper a review is given of the various scientific results which are at the basis of the modern progress in high-duty cast-iron production. The second part treats of the evolution of the practical side of the question during the last ten years. A sound basis of production of high-duty cast iron has been the semi-steel process developed during the war. Fairly good mechanical properties were obtained on test-bars, but they were not uniform in any section of a casting, which was a bad feature in the use of such material. The development of the electric furnace in foundries has given place to the single and duplex processes, giving the first real possibility of adopting compositions with low carbon and high silicon, leading not only to better properties but also to a good uniformity, and thence to more reliability. The careful study of melting steel scrap in cupolas for the duplex process, coupled with the knowledge of the fact that some kinds of scrap carburise slowly, has resulted in the establishment of an interesting cupola process. The final product is as uniform and reliable as if it were produced electrically. It is perhaps possible that cupola low-carbon cast iron can be further improved by taking and treating it in a "jarring" or, better, a "grating" forehearth. The low-carbon cupola process is not, technically speaking, an improvement on the duplex; its principal advantages are simplicity and that it may replace the duplex when the operation of an electric furnace is too expensive.

High-Test Grey Cast Iron. E. E. Marbaker. (Paper read before the American Foundrymen's Association, Apr. 1929). The author reviews European developments in the production of high-duty cast iron. The methods now known may be divided roughly into six classes, as follows: (1) Decrease of carbon content; (2) control of cooling rate after casting; (3) reduction of particle size of graphite and improvement of distribution: (a) superheating, (b) rapid cooling of high-silicon iron, (c) treatment with calcium silicide; (4) alloying with elements, such as nickel and chromium; (5) agitation of molten iron; and (6) eutectic cast iron. Each group is considered briefly.

Properties of Cast Iron are Related to its Structure. E. E. Marbaker. (Foundry, 1928, Vol. 56, Dec. 1, pp. 979-980). **Many Processes are Used to Produce High-Grade Castings.** E. E. Marbaker. (Foundry, 1928, Vol. 56, Dec. 15, pp. 1005-1007). **Improves Cast Grey Iron with Steel Scrap Additions.** E. E. Marbaker. (Foundry, 1929, Vol. 57, Jan. 1, pp. 10-12). A review of different methods for the production of high-duty cast iron.

Melting Practice in the Foundry. H. M. Lane. (Iron Age, 1928, Vol. 122, Nov. 29, pp. 1359-1362). A discussion of the factors involved in the production of high-grade iron with minimum fuel consumption. The use of powdered coal in cupolas, electric furnace practice, and the use of scrap are touched upon.

Eutectic Cast Iron. A. Mitinski. (Paper read before the International Foundry Congress, Paris, 1928: Foundry Trade Journal, 1928, Vol. 39, Dec. 6, p. 413). The author advocates the use of cast irons of eutectoid composition for high quality castings.

A Consideration of the Various Claims for Producing High-Class Cast Iron. H. J. Young. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1928, Vol. 39, Dec. 6, pp. 408-410). The author draws attention to the variations and irregularities that occur in the production of different castings, and emphasises the need for closer control of foundry operations and proper specifications.

The Manufacture of High Quality Cast Iron. B. Osann. (Foundry Trade Journal, 1928, Vol. 39, Dec. 20, pp. 448-450, 456). An English translation of an article which appeared in Die Giesserei, 1928, Vol. 15, July 6, pp. 648-655. (See Journ. I. and S.I., 1928, No. II. p. 311.)

The Development of High-Duty Cast Iron. F. D. Corbin. (Foundry Trade Journal, 1929, Vol. 40, Jan. 31, pp. 83-84, 94). A review of recent developments in the production of high-duty cast iron, with special reference to processes introduced in Germany.

Quality Cast Iron, Difficulties of its Production, and New Methods of Manufacture. Lincke. (Giesserei Zeitung, 1929, Vol. 26, Feb. 15, pp. 104-108). The author discusses progress made in the production of high-duty cast iron in the cupola, the electric furnace, and the rotating furnace; various types of furnaces are illustrated diagrammatically. Axially and eccentrically rotated furnaces are considered.

Does the Production of High-Duty Cast Iron in the Electric Furnace Require a Basic Lining? K. F. Krau. (Die Giesserei, 1929, Vol. 16, Jan. 25, pp. 88-91). The metallurgical aspect of the production of high-duty electric cast iron is reviewed. The silicon in the acid process effects a constant deoxidation and removal of gas, and so plays a decisive part in the refining process.

Ascendency of Alloy Iron Castings. E. F. Cone. (Iron Age, 1929, Vol. 123, Mar. 28, pp. 861-863, 924). The author surveys the developments in the manufacture and uses of alloy cast iron in America. Some foundries use alloy-bearing pig iron, others introduce the alloying element into the metal, either in the cupola spout or in the ladle, while others use alloy steel scrap in the cupola mixture. The use of castings with from 0.30 to 1 per cent. of molybdenum is extending rapidly.

Nickel-Alloy Cast Iron. H. Unger. (Giesserei Zeitung, 1929, Vol. 26, Apr. 1, pp. 181-188). The author discusses the following matters: German experiences with nickel-alloy cast iron; the

investigations of the International Nickel Co.; action of the nickel addition in refining the graphite and grain-size; the reduction of chilling effect; denser structure; raising of the Brinell hardness with simultaneously improved machinability; increased strength properties; resistance to wear.

Cleaning Room Progress Aids Production of Quality Castings.

F. G. Steinebach. (Foundry, 1928, Vol. 56, Nov. 1, pp. 893-895, 898; Nov. 15, pp. 943-946; Dec. 1, pp. 987-989). The continuation of a series of articles describing various types of equipment and methods used for the cleaning of castings (see Journ. I. and S.I., 1928, No. II. p. 313).

Removes Cores Hydraulically. J. Prendergast. (Foundry, 1928,

Vol. 56, Nov. 15, pp. 922-925). **Cleaning Castings Hydraulically.** J. Prendergast. (Iron Trade Review, 1929, Vol. 84, Feb. 14, pp. 456-459). A description is given of hydraulic methods for the cleaning of castings. The economics effected by the method are indicated.

Cleans Castings with Sand and Water. E. A. Custer, jun. (Foundry,

1929, Vol. 57, Apr. 15, pp. 339-342). **Cleaning Castings Successfully with Stream of Sand and Water.** E. A. Custer, jun. (Iron Trade Review, 1929, Vol. 84, Apr. 25, pp. 1118-1120). A method is described in which a fine stream of sand is enveloped in a water-jet and is used for the cleaning of castings.

Wet Cleaning. M. Maier. (Die Giesserei, 1929, Vol. 16, Mar. 1,

pp. 205-206). The castings cleaning plant at the works of Messrs. F. Müller at Esslingen is described. The economic aspect is touched upon.

MOULDS AND CORES.

Wood Patterns. F. C. Edwards. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Feb. 14, pp. 127-129). The author discusses the requirements of wood patterns from several points of view.

Some Notes on Patternmaking. J. Delaney and R. Ballantine. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Feb. 28, pp. 167-168).

Patternmaking. D. Taylor. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Mar. 7, pp. 179-180).

Progressive Working Methods in the Pattern Shop. H. Tillmann. (Die Giesserei, 1928, Vol. 15, Nov. 16, pp. 1157-1159). The author discusses the simplification of the work by suitable subdivision of the operations, and the better utilisation of the machinery.

The Making of Correct Patterns. S. Fürst. (Giesserei Zeitung, 1929, Vol. 26, Jan. 15, pp. 37-40). By means of examples the author indicates various points, by attention to which the pattern-maker can assist the foundryman to produce good castings.

Some Pipe Templates and Patterns. (Iron and Steel Industry, 1929, Vol. 2, Feb., pp. 137-138). Some notes on the making of pipe templates and patterns are given.

Symposium on Moulding Machines. (Foundry Trade Journal, 1929, Vol. 40, Mar. 14, pp. 201-203; Mar. 21, pp. 217-218). At a meeting of the Institute of British Foundrymen four short papers were presented describing the advantages of different types of moulding apparatus. A. S. Beech dealt with hydraulic machines; Hunter described pneumatic machines; F. J. Cook described adaptable machines; and D. Sharpe dealt with sand-slingers.

Semi-Permanent Moulds for Castings. J. F. Gaffney. (Iron Age, 1929, Vol. 123, May 2, pp. 1203-1204). A method of moulding hydraulic plungers is described and illustrated, which allows the removal of the castings without destroying the formation of the mould.

Water-Cooled Copper Moulds. (Metallurgist, 1928, Vol. 4, Nov. 30, pp. 169-170). An abstract of an article by W. Rohn (Zeitschrift für Metallkunde, 1927, Vol. 19, Dec., pp. 473-478. See Journ. I. and S.I., 1928, No. I. p. 827).

The Runner in Grey-Iron Casting. Unterhuber. (Giesserei Zeitung, 1928, Vol. 25, Dec. 1, pp. 680-682). Relative cross-sections of runners and risers, the relation of weight of casting to casting period, the maximum linear speed of metal permissible in the narrowest part of the mould, &c., are discussed. A special form of pouring gate is described, and its use illustrated; a "filter" is employed, by means of which the metal is run in without turbulence, and slag kept back.

Casting Technique and the Loading of the Mould. B. Osann. (Die Giesserei, 1928, Vol. 15, Dec. 7, pp. 1217-1225). The author develops a formula, based on theoretical principles, to calculate the time of casting; he then gives the results of three experiments made to test the formula in practice. He also deals with the temperature of the iron. He determines the load necessary to put on the cope to prevent it floating; in addition to the buoyancy there is also the pressure

due to the inrush of the molten metal, which is determined experimentally.

The Packing Properties and Power Required in Ramming and Jolting Moulds. A. Rodehüser. (*Die Giesserei*, 1929, Vol. 16, May 3, pp. 413-421). The behaviour of moulding sands during ramming and jolting is dealt with. In order to make visible the movement of the sand particles, layers of sand were sieved into a suitable box; plaster was sprinkled on each layer before the next was sifted in, so that the different layers might be distinguished afterwards. A weight was allowed to fall on the sand, and the sand mass was then sectioned so as to expose half the weight embedded in the sand. It could be seen that the weight had sheared through the first layers; below that the layers were compressed and displaced downwards, the compression and displacement decreasing until at a certain depth below the weight the sand was not disturbed at all. Lateral disturbances were investigated by arranging the sand and plaster layers vertically. The power required to compress moulds in relation to their height, the power required for jolting, the influence of grain-size and moisture on the work of compression, and the resistance to compression were investigated.

The Production of a Mould in Four Parts by Means of Templates. R. Loewer. (*Die Giesserei*, 1928, Vol. 15, Dec. 21, pp. 1274-1276).

Casting Design Yields Savings. D. G. Anderson. (*Iron Age*, 1929, Vol. 123, Mar. 28, pp. 868-871). The importance of correct design of castings is pointed out, and several typical examples of improved moulding practice are described and illustrated. A new type of shake-out device is also described.

Rational Moulding with Stripping Plates. C. Schrage. (*Giesserei Zeitung*, 1929, Vol. 26, Apr. 15, pp. 219-220).

Inspection of Moulds in the Making. P. R. Ramp. (*Iron Age*, 1929, Vol. 123, Feb. 21, pp. 533-535). The author points out the importance of periodic inspection of moulds, and describes a system in operation at an American plant.

Venting and Gas Pressure in Moulds. R. D. Welford. (Paper read before the Institute of British Foundrymen: *Foundry Trade Journal*, 1929, Vol. 40, Apr. 11, pp. 266-268). Uniformity of grain-size has a very important bearing on the venting of moulds. The amount of moisture is of equally great importance, as it is evident that in addition to increasing the permeability, the more moisture there is the more steam is likely to be generated. By mechanical ramming a mould or core can be produced of even density, the sand

being evenly packed all round and over the pattern. This is a great advantage compared with the uneven hand-ramming. The venting of bottoms is best done by laying down a cinder or ash bed; this bed should be about 6 to 9 in. below the surface of the pattern and from 4 to 6 in. thick, and covered over with hay, straw, or other material to keep the bed clear from sand.

The Venting of Dry-Sand Moulds. E. Flower. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Apr. 18, pp. 285-286).

Mould Handling. R. J. Heisserman. (Paper read before the American Foundrymen's Association, Apr. 1929). The development and application of mould conveyors in foundries are discussed, and their advantages are pointed out.

The Standardisation of Moulding Boxes. A. Riebold. (Die Giesserei, 1929, Vol. 16, Mar. 15, pp. 249-254).

The Surface Conditions of Castings as Affected by Core-Sand Mixtures. H. L. Campbell. (Transactions of the American Foundrymen's Association, 1928, Vol. 36, pp. 461-468). Particulars are given of an investigation carried out to determine the factors which control the smoothness of the surfaces of castings which are formed by cores. The results indicate that the most desirable properties for dry-sand cores are obtained when the core sand contains grains of uniform size and of sufficient fineness to produce the required smoothness on the surfaces of the cores. The smoothness of castings which are formed by contact with cores will be practically the same as the smoothness of the cores, provided the metal is sufficiently fluid when it is poured to fill the minute cavities on the cores. The additions of bank sand or other finely divided materials to core-sand mixtures within reasonable proportions do not improve to any appreciable extent the smoothness of the surfaces of castings made in contact with these cores.

The Combination of Cores for Castings. W. Schwanert. (Die Giesserei, 1928, Vol. 15, Nov. 9, pp. 1133-1134). The author advocates, where possible, the combination of the cores for castings, in order to lessen the work of inserting them in the moulds. He gives examples of cases in which this can be done.

Accuracy Governs Core-Making Processes in Automobile Foundry. F. G. Steinebach. (Foundry, 1928, Vol. 56, Dec. 1, pp. 956-960; Dec. 15, pp. 1008-1012). An illustrated description is given of the core department of the Packard Motor Car Co., Detroit. The methods of handling and mixing core sand and the equipment and processes used in producing cores are described.

Pointers for the Successful Production of Oil-Sand Cores. W. West. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Apr. 18, pp. 287-299). The subject is discussed under the following headings: binding agents and equipment; sand drying and delivery; general notes on oil-sand binders; core drying; and core ovens.

Baking Practice for Oil-Sand Cores. H. L. Campbell. (Paper read before the American Foundrymen's Association, Apr. 1929). The author deals with baking practice for cores prepared with raw linseed oil. The changes during the baking period and the effects of temperature and time of baking on the strength of the cores are discussed. Oil-sand cores may be placed directly in core-ovens which are maintained at maximum baking temperatures, without injuring the cores. The total baking time may be decreased by using a minimum amount of moisture or volatile oils in the core-sand mixtures. The presence of oxygen is essential to the hardening of the cores. The length of time during which the cores are kept at maximum baking temperatures has a critical effect on the strength. The higher the temperature at which the cores are baked, the more limited is the range of time over which high strengths can be obtained. The removal of the gaseous products which are given off during the oxidation of linseed oil is essential to the rapid and complete hardening of the cores.

Converting Core-Ovens to Gas Heating. J. F. Langner. (Iron Age, 1928, Vol. 122, Dec. 6, p. 1424). Brief particulars are given of the change over of an installation of core-ovens from coke-firing to gas-firing. The benefits accruing from gas-firing are pointed out.

Continuous Ovens Increase Capacity and Speed Production. E. Bremer. (Foundry, 1929, Vol. 57, Jan. 15, pp. 82-85). An illustrated account is given of the methods of making, baking, and handling large cores for domestic boiler construction at the plant of the American Radiator Co., Buffalo.

The Efficiency of Foundry Drying Chambers. O. Ebling. (Die Giesserei, 1929, Vol. 16, Jan. 11, pp. 27-37; Jan. 18, pp. 56-61; Jan. 25, pp. 80-88; Feb. 1, pp. 105-111). Thermal balances for 8 drying chambers are presented and discussed, and the evaluation of the efficiency is considered.

Baking Cores in Gas-Fired Ovens. J. B. Nealey. (Heat Treating and Forging, 1929, Vol. 15, Feb., pp. 223-225). The core-making section of the Bond plant, Buffalo, of the American Radiator Co. is equipped with conveyors, ovens, and moulding machines arranged to synchronise the two operations of making and baking. The whole foundry is laid out for "straight-line" mass production.

Core Tests Show Peculiar Results. G. J. Corrigan. (Foundry, 1929, Vol. 57, Feb. 15, pp. 144-145). The author has investigated the condition of cores at time of pouring the casting. Most cores lose 60 per cent. of their strength when buried in moulding sand for 24 hr., and it is indicated that old moulding sand contains a chemical agent which attacks the core much more rapidly than moisture.

MOULDING SANDS.

The Testing of Moulding Sand in Theory and Practice. F. Roll. (Die Giesserei, 1929, Vol. 16, Apr. 26, pp. 393-401). The relationships between gas permeability, strength, sedimentation, adsorption, &c., of moulding sands are discussed, and methods of testing are described.

Investigation of Moulding Sand. H. Nipper and E. Piwowarsky. (Die Giesserei, 1929, Vol. 16, Mar. 8, pp. 219-225; Mar. 15, pp. 237-249). The results of an investigation of the physical characteristics and properties of moulding sand are tabulated.

Investigations into Moulding Sands. (Foundry Trade Journal, 1929, Vol. 40, Jan. 24, p. 63). An abridged translation of the above report giving results of an investigation by H. Nipper and E. Piwowarsky on the permeability of moulding sands.

The Gas Permeability of Moulding Sands. F. Maske and E. Piwowarsky. (Foundry Trade Journal, 1929, Vol. 40, Mar. 28, pp. 233-236). An English translation of a report describing experiments in which the volumes of the gases liberated during the making of castings were determined. The original report appeared in Die Giesserei, 1928, Vol. 15, June 15, pp. 559-566. (See Journ. I. and S.I., 1928, No. II. p. 317.)

Moulding Sands. L. R. Dunn. (New Zealand Journal of Science and Technology, 1928, Vol. 10, July, pp. 74-79). The author records the results of tests for physical properties made on 15 New Zealand moulding sands.

Some Experiences in Sand Control. E. F. Wilson. (Paper read before the American Foundrymen's Association, Apr. 1929). The author discusses a number of factors to be taken into account when carrying out tests on moulding sands.

The Reclamation and Reconditioning of Foundry Sands. W. E. Dennison. (Foundry Trade Journal, 1928, Vol. 39, Dec. 20, p. 447).

The subject is dealt with under the following headings: influence of cost, use of rational analysis, sieving tests, moisture determination influenced by carbon content, and steps to safeguard deterioration.

Some Factors in the Production of Sound Grey Iron Castings. R. W. Kurtz and K. S. Clow. (Paper read before the American Foundrymen's Association, Apr. 1929). The authors describe the practice at the plant of James B. Clow & Sons, Chicago, for the production of sound castings. An outline is given of the moulding sand tests employed, and melting and pouring practice. Descriptions are given of a combination permeability and tensile test, and a "blowability" test for moulding sand.

The Latest Advances in Sand Preparation. W. Emrich. (Die Giesserei, 1928, Vol. 15, Dec. 7, pp. 1229-1231). The author discusses the development of wet methods for the preparation of sand, and describes several machines.

The Spermolin Sand-Mixing Machine. (Iron and Steel Industry, 1928, Vol. 2, Nov., p. 62). The sand is rotated and conveyed to the centre of the container by right- and left-handed scrolls working on a common shaft. The sand is well rubbed together and mixed with the required oil, but without being crushed to powder. The machine is both rapid and economical in operation.

The Influence of Drying on the Properties of Used Sands. H. Pinsl. (Die Giesserei, 1929, Vol. 16, Mar. 29, pp. 285-291). Tables and diagrams showing the interrelationship of various properties, such as the binding power, the gas permeability, the moisture, &c., are given.

New Form of Riffle Dryer for the Preparation of Sand. M. Weiss. (Die Giesserei, 1929, Vol. 16, Feb. 8, pp. 132-134). The author discusses in detail the heat required for drying sand. He illustrates and describes briefly a new form of dryer. This consists of a long hollow horizontal cylinder, fired at one end; the sand is fed in near the firing end and travels towards the other end, moving in the same direction as the hot gases. Attached to the inside of the cylinder are a number of riffle plates; as the cylinder revolves about its axis the sand is continually poured over the edges of the ruffles, in thin streams, through the hot gases, so that drying is accelerated and is more efficient.

Reducing New Sand Consumption in the Steel Foundry. H. A. Mason. (Transactions of the American Foundrymen's Association, 1928, Vol. 36, pp. 549-562). The methods employed at an American foundry for controlling and reclaiming foundry sand are described.

SPECIAL CASTINGS.

Forty Years of Progress Marks Career of Engine Plant. P. Dwyer. (Foundry, 1929, Vol. 57, Feb. 1, pp. 94-99). The methods employed in the moulding and casting of gas engine and Diesel engine parts at the foundry of the Superior Gas Engine Co., Springfield, Ohio, are described and illustrated.

Material of the Piston Heads of Large Diesel Engines. P. Wolff. (Die Giesserei, 1929, Vol. 16, Feb. 8, pp. 121-125). The structure and other features of piston heads for Diesel engines of large ships have been examined. The investigation shows that, without making use of the patented processes for the production of high-duty cast iron, a foundry can produce a comparable product for special purposes.

Heavy Boiler Sections are Made on a Production Basis. E. Bremer. (Foundry, 1928, Vol. 56, Nov. 1, pp. 881-884, 897). The methods used at the plant of the American Radiator Co. for the moulding and casting of domestic boiler sections are described and illustrated.

Chilled Castings. H. Bator. (Iron and Coal Trades Review, 1929, Vol. 118, Apr. 5, pp. 496-497; Foundry Trade Journal, 1929, Vol. 40, May 9, pp. 339-340). The author discusses the characteristics of chilled castings, selection of material, importance of analysis, hardness determination, and characteristic structures. One of the chief requirements of a good chilled casting is that the hard white layer must merge into the softer grey portion not only very gradually, but also in finely penetrating and slightly radiating lines.

Cast-Iron Rolls. (Iron and Steel Industry, 1929, Vol. 2, Feb., pp. 131-135; Mar., pp. 163-164). After a reference to the history of roll casting, the casting of chilled rolls is described. The nature of the moulds, the selection of the metal for the rolls themselves and its composition, and the part played by the low-silicon pig iron which is preferred for the purpose, are discussed. A table of chemical compositions of rolls is appended.

Rolling-Mill Rolls: A Bibliography. V. S. Polansky. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Mar., pp. 431-435; Apr., pp. 569-573; May, pp. 694-696). A bibliography of literature dealing with the design and manufacture of rolls. Articles dealing with roll failures are included.

Making Rolls for Paper Calenders. W. S. Huson. (Iron Age, 1929, Vol. 123, Jan. 24, pp. 265-268). The manufacture of chilled rolls for paper-calendering machines is described. The rolls are cast on end, and the depth and character of chill is of extreme importance.

Alloyed Cast-Steel Chains. H. K. von Scheele. (*Die Giesserei*, 1929, Vol. 16, Mar. 29, pp. 294-295). The author discusses the use of alloy steels for casting chains, and describes a mould for casting simultaneously several interlinked links of a chain. The chain is built up by inserting half of an end link of a previously cast section of the chain into the ends of the mould. A hard manganese steel (C 1·15, Mn 12·20, Si 0·30, P 0·07 per cent.) with 10-mm. links broke under a load of 8680 kg.; it had been quenched from 1050° C. in cold water and then tempered for 2 hr. at 200° C.

Alloyed Cast Iron as Raw Material for Tubes. (*Röhrenindustrie*, 1929, Vol. 22, Jan. 3, pp. 3-4).

The Arrangement of the Pattern for Making the Mould for a Cast-Steel Wheel. F. König. (*Giesserei Zeitung*, 1929, Vol. 26, Mar. 1, pp. 132-136). The author discusses all the pattern-makers' problems that arise in the preparation of the mould for a cast-steel wheel, and gives explanations for the procedure adopted.

The Manufacture of Cast-Steel Anvils. H. K. von Scheele. (*Giesserei Zeitung*, 1929, Vol. 26, Jan. 1, pp. 15-16).

Practical Moulding. A Contribution towards the Economy of Patterns. A. Zankl. (*Die Giesserei*, 1929, Vol. 16, Mar. 22, pp. 265-266). The author describes the moulding of a pipe, 2 m. long with six flanged branches, without the use of a pattern.

Some Interesting Moulding Jobs. E. Longden. (Paper read before the Institute of British Foundrymen: *Foundry Trade Journal*, 1929, Vol. 40, Apr. 18, pp. 283-284; Apr. 25, pp. 301-304). The operations involved in moulding a large centrifugal pump body, a pulping-machine jacketed cylinder, and a carding-engine cylinder are described and illustrated.

CENTRIFUGAL CASTING.

Centrifugal Casting of Diesel Engine Parts. J. E. Hurst. (*Fonderie Moderne*, 1928, Vol. 22, May 25, pp. 193-198). The author describes the centrifugal casting process, its advantages, the types of moulds used, and the properties of the castings.

A Notable Foundry. (*Iron and Steel Industry*, 1928, Vol. 2, Dec., pp. 69-71). The centrifugal casting plant of Messrs. Newton Chambers & Co., Ltd., Thorncliffe Ironworks, where the Hurst-Ball Spun Sorbitic process is employed, is described and illustrated.

The Centrifugal Casting of Iron Pipes. E. J. Fox and P. H. Wilson. (Paper read before the Co-ordinating Societies, Birmingham, Jan. 8, 1929: *abstract*, Iron and Steel Industry, 1929, Vol. 2, Feb., pp. 147-150). A description of the plant and methods employed by the Stanton Iron Co., Ltd., for the centrifugal casting of pipes.

Centrifugal Casting. J. Ladouce. (Arts et Métiers, 1929, Vol. 82, Apr., pp. 121-131). The author discusses the principles, the history, and modern methods of carrying out the centrifugal casting of pipes.

Briede Process of Pipe-Casting. (Iron and Steel Industry, 1928, Vol. 2, Nov., p. 52). A brief note of the centrifugal pipe-casting machines in use at Gelsenkirchen.

New Foundry for Centrifugally Cast Pipes by the Moore-Wood Process. J. Mehrrens. (Giesserei Zeitung, 1929, Vol. 26, Feb. 1, pp. 83-87). The new centrifugal pipe foundry of Messrs. R. D. Wood & Co., Florence (N.J.), is described. Sand moulds are used.

STEEL FOUNDRY PRACTICE.

Produces Alloy Castings to Withstand Severe Service. H. R. Simonds. (Foundry, 1929, Vol. 57, Mar. 1, pp. 180-183). Particulars are given of the production of nickel and alloy steel castings for corrosion and heat resistance as carried out at an American plant.

Axle Housings of Electric Steel. E. Favary. (Iron Age, 1929, Vol. 123, Feb. 14, pp. 477-478). The author describes electric furnace practice for the production of axle housings. These castings contain about 0.30 to 0.31 per cent. of carbon and 1 per cent. of nickel.

High-Manganese Steel. A. Manuelli. (Ingegneria, 1927, Vol. 6, Nov., pp. 382-389). The author discusses the manufacture of high-manganese steel, and deals with its use for the making of castings, adding comments on the most suitable moulding materials. He touches also on the mechanical properties of the steel.

MALLEABLE CAST IRON.

Malleable Cast Iron. C. H. Plant. (Iron and Steel Industry, 1928, Vol. 2, Nov., pp. 53-55; Dec., pp. 89-90, 94; 1929, Vol. 2, Jan., pp. 117-119; Feb., pp. 151-152; Mar., pp. 175-176). The continuation of a series of articles (*see* Journ. I. and S.I., 1928, No. II.

p. 323). In the present instalments the author deals with the melting of whiteheart iron, and gives details concerning the structure and operation of the cupola. He then turns to the annealing of whiteheart castings, and discusses all aspects of the process, including the use of regeneration, types of furnaces, systems of charging, cleaning practice, annealing boxes, the theory of the process, the removal of carbon, effects of impurities, retardation of graphitisation defects in castings, and mechanical tests. The author next gives attention to the blackheart process, and discusses the composition of the raw material, the influence of impurities, the furnaces used for melting and their fuels.

The Importance of the Brackelsberg Furnace for the Foundry, in Particular for the Production of High-Duty Cast Iron. P. Bardenheuer. (Die Giesserei, 1928, Vol. 15, Nov. 23, pp. 1169-1173). A diagram of the Brackelsberg furnace is reproduced. The furnace body is a horizontal cylinder with axial openings at each end; it is heated from one end by pulverised coal, the air-blast being preheated by the waste gases issuing from the other end. The furnace body is tipped lengthwise for charging, and can be given a rocking motion about its axis. For the method of firing it is claimed that the fuel ash and sulphur do not enter the metal; the excess air is reduced to a minimum, and, consequently, the temperature attained is very high and melting is rapid. Rocking the furnace brings cold material into the hotter parts. Up to a point not much above the melting point of the iron, the solubility of oxide in the metal is low, and it is therefore able to enter the slag. As soon as melting is complete the metal is covered with a slag, lime being added for the purpose; sufficient slag is formed to protect the metal without acting as a heat insulator. Solution of gases and oxides is thus reduced; in the ladle the metal lies quiet without the evolution of gases. The superior qualities of iron melted in this furnace and the advantages of the method of melting for the production of high-duty cast iron and malleable cast iron are discussed very fully.

The Coal-Dust Fired Rotating Furnace Compared with the Cupola for the Production of High-Duty Malleable Iron. H. Kalpers. (Giesserei Zeitung, 1929, Vol. 26, Feb. 1, pp. 78-82). The Brackelsberg furnace is described, and its advantages for the production of high quality malleable iron are considered.

Coal-Dust Rotary Furnace *versus* the Cupola for the Production of High Quality Malleable Iron. H. Kalpers. (Foundry Trade Journal, 1929, Vol. 40, Apr. 4, pp. 257-258).

Duplex Plan Reduces Melting Time. B. Finney. (Iron Age, 1929, Vol. 123, Feb. 7, pp. 397-399). Particulars are given of the duplex melting system adopted by the Southern Malleable Iron Co., East St.

Louis, Illinois. Iron is melted in a cupola and discharged through an open spout into the rear of an air furnace, where the first stage of refining is carried out. This refining zone is separated from the main part of the furnace by a bridge wall of firebrick and silica sand. In construction the cupola does not depart from the usual design. However, by manipulating the blast, it is possible to close down the cupola, stop melting, and start again without dropping the bottom. Upper and lower tuyeres of the cupola are used alternately in order to change the melting zone and bring about proper slagging conditions. A small container supplied with a desulphurising compound in powdered form is mounted on the blast-pipe of the cupola and the compound enters the cupola with the blast. In the air furnace the two zones are connected by a short spout through openings in the side wall. When the metal is ready to be transferred from the first to the second refining zone, the operator taps out the metal in the same manner as in the old-style furnace. A steam pipe is provided outside the opening of the first refining zone. The steam is directed against the surface of the molten metal as it passes from one zone to the other, forcing the slag back and causing it to flow through a side trough constructed for that purpose.

Production of Malleable Castings. F. H. Hurren. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, Jan. 10, pp. 33-36). The author describes moulding practice and the subsequent annealing process for the production of whiteheart malleable iron.

The Heat Treatment of Malleable Cast Iron. H. A. Schwartz. (Fuels and Furnaces, 1929, Vol. 7, Feb., pp. 187-191). The subject is discussed under the following headings: formation of graphite in cast iron, the conversion of the carbon, graphitising temperature, and furnaces used in heat-treating malleable castings.

Practical Aspects of White-Fracture Malleable. D. P. Forbes. (Paper read before the American Foundrymen's Association, Apr. 1929). The author describes the white fracture which sometimes appears in blackheart malleable cast iron, and the conditions under which it occurs. Certain remedies for its avoidance, and a possible metallurgical explanation of the phenomenon, are put forward.

FOUNDRY PLANT.

Farrington Foundry Leyland Motors, Ltd. (Iron and Coal Trades Review, 1929, Vol. 118, Jan. 4, pp. 1-2). The equipment of this iron

and steel foundry is described and illustrated. Electric arc furnaces are used in the steel melting shops.

Automobile Foundry Practice. (Automobile Engineer, 1929, Vol. 19, Mar., pp. 82-87). The foundries of the Midland Motor Cylinder Co., Ltd., and of the Birmingham Aluminium Casting (1903) Co., Ltd., are illustrated and described.

The Chevrolet Foundry at Saginaw, Mich., Division of the General Motors Corporation. F. E. Grützmaier. (Die Giesserei, 1928, Vol. 15, Nov. 16, pp. 1150-1157; Nov. 23, pp. 1173-1182). The foundry, which is laid out for the mass-production of castings, is described and illustrated.

Lumber Company Makes Castings. C. Babbie and L. O. B. Lindstrom. (Iron Age, 1929, Vol. 123, Jan. 31, pp. 335-337). Particulars are given of the equipment of the new foundry of the Red River Lumber Co., at Westwood, California. The foundry is operated electrically throughout and produces iron, steel, and non-ferrous castings.

The Addition of a Steel Foundry to an Open-Hearth Steelworks. A. F. Hager. (Die Giesserei, 1929, Vol. 16, Mar. 29, pp. 291-294). The author describes the erection and equipment of a steel foundry which was to obtain its liquid steel from the open-hearth steelworks alongside which it was built.

Efficient Steel Casting Grinding. F. A. Lorenz, jun. (Paper read before the American Foundrymen's Association, Apr. 1929). The author discusses the efficient grinding of steel castings and describes the experience at his own plant. Comparative costs of grinding by two methods are tabulated.

Equipment Saves Time and Floor Space. P. Dwyer. (Foundry, 1929, Vol. 57, Apr. 15, pp. 316-321, 329). The mould-conveying and sand-distributing equipment at the plant of the Sandwich Foundry Ltd., Sandwich, Ontario, are described and illustrated.

Materials Handling in Grey Iron Foundries. A. Walton. (Paper read before the American Foundrymen's Association, Apr. 1929).

Transport in the Small Foundry. M. Escher. (Die Giesserei, 1929, Vol. 16, Apr. 19, pp. 380-381).

Electric Trucks in the Foundry. Lucas. (Die Giesserei, 1929, Vol. 16, Apr. 19, pp. 365-375). A number of electrically propelled trucks and wagons for transporting materials in a foundry are illustrated and discussed.

Travelling Cranes in the Foundry, in Particular Working Speeds and Control of Travelling Cranes. Hubert. (*Die Giesserei*, 1929, Vol. 16, Apr. 12, pp. 353-358).

COOLING PHENOMENA AND DEFECTS IN CASTINGS.

The Metallurgy of Steel Castings. A. McCance. (Paper read before the Institute of British Foundrymen, and Institution of Mechanical Engineers : *Foundry Trade Journal*, 1928, Vol. 39, Dec. 27, pp. 465-466 ; 1929, Vol. 40, Jan. 10, pp. 25-26). The author discusses the phenomena of the contraction of steel castings. The three stages are dealt with—liquid, solidifying or freezing, and cooling contraction.

Shrinkage in White Cast Iron. H. A. Schwartz. (Paper read before the American Foundrymen's Association, Apr. 1929). The author discusses the formation of porous spots during the freezing of white cast iron. The mechanism by which these spots are formed is first considered. The available data, regarding the changes of density at the freezing point of iron, are briefly reviewed, a method for the direct determination of this type of shrink is described in detail, and a series of results on commercial heats is given, showing that although carbon and silicon content affect shrinkage slightly there are variables of much greater magnitude which have not been worked out. The subject is treated entirely from a metallurgical viewpoint, and no attention has been given to the design of patterns.

Will Shrinkage Test Show Pig Iron Quality ? E. J. Lowry. (Paper read before the Association Technique de Fonderie de Belgique : *Foundry*, 1929, Vol. 57, Mar. 15, pp. 228-230). It is indicated that blast-furnace practice influences the quality of the pig iron produced and bears some relationship to shrinkage encountered in castings.

What Conclusions can the Foundryman Draw from Diagrams of the Specific Volume Changes of Metals ? P. Kroll. (*Revue Technique Luxembourgeoise*, 1929, Vol. 21, Jan.-Feb., pp. 8-10). The author discusses the effects of shrinkage and contraction—as revealed by specific volume curves—in the molten, semi-molten, and solid states on the porosity, tendency to pipe, and liability to contain blowholes, of the cast metal.

Internal Stresses. A. Le Thomas. (Paper read before the International Foundry Congress, 1928 : *Foundry Trade Journal*, 1928, Vol. 39, Dec. 6, pp. 414-415). Stresses in castings and means for their elimination are discussed.

Thermal Cracks in Steel Castings. K. Singer. (Die Giesserei, 1928, Vol. 15, Dec. 7, pp. 1225-1229).

The Influence of Casting Temperature on Chilled Castings. F. Busse. (Die Giesserei, 1929, Vol. 16, Feb. 22, pp. 169-179). The author discusses the factors governing the crystallisation process in chilled castings, such as chilled rolls. He has collected together a number of observations from practice, and has constructed frequency curves relating to the formation of cracks and blowholes, depth of chill, and types of structure. Within the casting temperature interval 1220° to 1320° C., the supercooling and speed of crystallisation in the outer zone increases with rising casting temperature; away from the wall, however, the speed of recrystallisation is greater with cold casts. With different silicon contents the influence of the casting temperature on the depth of chill is variable. With very hot casts the speed of crystallisation is so rapid that few nuclei form; the resulting crystals are fine needles, and the metal is brittle. With lower casting temperatures the structure is better. No connection could be traced between the casting temperature and the occurrence of cracks. A low casting temperature (1220° to 1200° C.) was conducive to the formation of blowholes in the outer zone.

Sponginess in Cast Irons. J. Butterworth. (Paper read before the Institute of British Foundrymen: Foundry Trade Journal, 1929, Vol. 40, May 16, pp. 362-363). The author discusses the occurrence of pinholes resulting from occluded gases and dirt holes caused by oxidation of the metal.

Waster Castings: their Lesson and their Prevention. A. E. M. Smith. (Foundry Trade Journal, 1928, Vol. 39, Dec. 13, pp. 429-430).

PRODUCTION OF STEEL.

STEEL-MAKING PROCESSES.

Proposed Basic Bessemer Process at the Kerch Works. V. Grum-Grijailo. (Journal of the Russian Metallurgical Society, 1928, No. 1, pp. 77-84). (In Russian.)

The Kühn System of Regeneration. Thaler. (Feuerungstechnik, 1928, Vol. 16, June 1, pp. 123-125). It is pointed out that the gases leaving the ordinary type of open-hearth regenerator have frequently a temperature higher than 800° C.; this is recoverable by means of waste-heat boilers, provided that there is a use for all the steam produced. There are, in addition, other inconveniences of this system: The output of the boilers is the inverse of that of the furnace; fusion of the upper part of the checker work leads to stoppages and consequent falls of temperature in the furnace hearth; the operation of the furnace is irregular; and maintenance costs are high. The Kühn regenerator is much taller than the normal, and the section is reduced as the gases cool off. The first checker work is of silica brick. Practical operating results are given (*see also* Journ. I. and S.I., 1928, No. I. p. 810).

The Construction of Ports of Open-Hearth Furnaces. V. Balabanoff. (Journal of the Russian Metallurgical Society, 1928, No. 1, pp. 129-138). (In Russian.)

The Isley Furnace Control. G. A. Merkt. (Iron and Steel Engineer, 1929, Vol. 6, Apr., pp. 164-172). The author describes the Isley furnace control as applied to open-hearth furnaces, and gives particulars of operating results and economies obtained.

Electric Open-Hearth Door Hoists. (Iron Age, 1929, Vol. 123, Feb. 7, pp. 413-414). Illustrated particulars are given of the Blaw-Knox electric door hoist. The hoist is situated at the back of the furnace. A motor operates the main shaft which in turn actuates the pulley sheaves on which are wound the cables leading to the various furnace doors. These cables cross the furnace top and carry the door on one end and a counterweight on the other end. By this arrangement the cables are always taut, and there is no play or lost motion between the counterweight and the door. To open a certain door the

operator presses the button corresponding to that door, and also a button to start the motor. The operator has complete control, being able to move any door in either direction any desired amount.

Large Open-Hearth Steel Furnaces. F. A. King. (Paper read before the American Iron and Steel Institute, May 1929). Perhaps the more important advance in the development of open-hearth capacity has been in furnaces installed during the last few years. The open-hearth plant of the Weirton Steel Co. includes 12 stationary furnaces of from 150 to 350 tons capacity. The hearth dimensions are approximately as follows :

Furnaces.		Tapping. Tons.	Bath Length. Ft.	Bath Breadth. Ft.	Hearth Area. Sq. ft.
Nos. 1 to 6	.	150	40	16	615
„ 7 to 10	.	250	45	17	720
No. 11	.	300	49	19	860
„ 12	.	350	55	19	992

Experience at Weirton indicates a tendency to increased yield in the product of the larger furnaces. Oxidation in the deeper bath is not quite so extensive as in the shallower. Less bottom trouble has been found as the size or depth of bath increases. With the deeper bath the bottom cleans better and is more easily kept in proper condition, and in practice the larger furnaces have given less bottom trouble.

There is no question that there is a limit to the size of open-hearth furnaces, as there is to blast-furnaces. But it is believed with large open-hearth furnaces that the limit in size has not been reached. To keep pace with the modern trend of all industries, furnaces will be built even larger than the Weirton 350-ton furnace, which is the largest stationary open-hearth furnace in operation or projected.

Possibilities of Improving the Heat Economy of Open-Hearth Furnaces. M. Tigerschiold. (Jernkontorets Annaler, 1928, Vol. 111, pp. 71-103).

Operation of Open-Hearth Furnaces. (Iron Age, 1928, Vol. 122, Nov. 22, pp. 1294-1298; Nov. 29, pp. 1366-1368). A digest is given of the proceedings of the Pittsburgh Meeting of the Open-Hearth Committee of the American Institute of Mining and Metallurgical Engineers. A number of problems in connection with the design and operation of open-hearth furnaces were discussed, and a brief description is given of the 25-ton acid-lined furnace at Indiana Harbour, which is designed on the Stevens principle. This furnace is built largely of structural steel, is covered with steel plate to the floor line or above, and is insulated. The covering includes the regenerators and slag pockets. The chambers are under the hearth of the furnace, and have 13 ft. depth of checker brick with a top area 9 ft. 6 in. square. The top layers of the brickwork are silica and the lower portion clay. Air

is supplied by means of a fan controlled by a Stevens valve. The accumulations of slag were reported to be very small—only about 6 in. in each pocket—and about 1 in. of dirt on the checker work. Fuel consumption of 44 to 56 gal. to the ton was reported to have been reduced on the first 500 heats to 23.68 gal.

Review of Modern Open-Hearth Practice. G. D. Tranter. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 69–74, 80). A résumé of developments in equipment and methods employed in the basic open-hearth process in America.

Modern Open-Hearth Practice in Germany. F. Stein. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Mar., pp. 409–414). The author reviews the progress which has been accomplished in German open-hearth plants during the last few years. Important features in furnace design such as the Hoesch and Moll furnaces and the Kühn chamber are dealt with. The application of fuels and the correct proportioning of the charge are also discussed. The new classes of steel developed for structural purposes are touched upon.

Recent Progress in Steel Manufacture Abroad. J. K. Hoyt. (Iron and Steel of Canada, 1929, Vol. 12, Jan., pp. 28–29). A brief report of observations made during a recent visit to important steel-making centres in England and Sweden.

Calculation of Carbon Balance of Metallurgical Furnaces. R. D. Pike. (Industrial and Engineering Chemistry, 1928, Vol. 20, Dec., pp. 1356–1361). The author describes the application of stoichiometry to the development of a complete carbon balance, and incidentally the fuel balance, of a type of metallurgical furnace in which account is taken of the possibility of leakage outwards from certain parts of the furnace of carbon-bearing gases.

Manufacture of Thick-Skinned Ingots of Rimming Steel. H. D. Hibbard. (Fuels and Furnaces, 1928, Vol. 6, Nov., pp. 1527–1530; Dec., pp. 1687–1689; 1929, Vol. 7, Jan., pp. 67–69; Feb., pp. 235–237; Mar., pp. 395–397). A series of articles describing the manufacture of thick-skinned ingots of rimming steel by the open-hearth process. The first article deals with gas holes in rimming steel, typical ingots, and the primary and secondary skin. The second article describes the general procedure of open-hearth furnace operation for the production of this type of steel. The third article deals with the control of the temperature of the bath. The fourth article contains a discussion of the three kinds of gas holes that are present in rimming steel, their formation and effect on the steel. In the fifth article the characteristics of the ingots and the influence of speed of teeming are dealt with.

Physical Chemistry of Rimmed Steel. J. E. Carlin. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 261-262). The practice in producing rimmed steel in the open-hearth furnace is outlined. The amount of carbon monoxide present in steel before the addition of manganese is dependent on temperature only, and independent of carbon and ferrous oxide content. High-carbon steels after the addition of manganese contain less gas (CO) than low-carbon steels, and for this reason it is impossible to rim high-carbon steels. The evolution of gas (CO) depends upon actual solidification of the metal. Carbon content and temperature are the most important factors in the manufacture of rimmed steel.

Making Large Plates of Alloy Steel. (Iron Age, 1928, Vol. 122, Dec. 13, pp. 1492-1494). The manufacture of nickel steel plates containing between 2 and 3 per cent. of nickel is described. During melting it is only necessary to use ordinary precautions to ensure a good sound steel. Nickel is added in the forms of nickel steel scrap and metallic nickel. Either the acid or basic process may be used. The killing of the steel is of primary importance since blowholes in the ingot do not weld up satisfactorily. This is accomplished by the addition of silicon, manganese, and aluminium to the bath or ladle. The design of the mould is of great importance, and a mould with fluted walls gives excellent results. The greatest care is necessary in pouring to avoid such defects as splashes, laps, stop-pours, and mould pulls. While bottom-pouring has been largely employed in the production of deck-plate armour of this analysis, the recent trend is towards top-pouring, using great care to avoid splashes. The ingot should be stripped from the mould as soon as it has solidified, and placed immediately in a pit to protect the outer surface from chilled air. The pit should remain at approximately the temperature of the ingot for about 1 hr. and then should be gradually heated to 2150° F. with a smoky flame. If the ingot gets too hot or an oxidising flame is used, the original scale will fall off, and during rolling it will be extremely difficult to clean the plate of the second scale which forms. The cleaning of the plate during rolling is best accomplished by high-pressure water, salt, and old burlap soaked in brine. In the process of rolling the ingot is first given one or two passes in a longitudinal direction to "sadden" the ingot. It is then cross-rolled for width. When the ingot is reduced to about one-half in thickness and to a size suitable for reheating, it is cooled and inspected. It is then chipped with pneumatic chisels to remove serious surface defects, although often the entire top and bottom surface is planed off, an expensive treatment which is frequently justified. The clean slabs are then reheated and finished on a 4-high reversing mill. When the plate has been subjected to the heavier drafts, and after the top surface has been cleaned with burlap and salt, it is turned over so that the bottom surface may be cleaned while rolling is completed. The best combination of physical

properties in nickel steel plates is obtained if they are finished at a good red heat (1450° to 1500° F.) and allowed to cool slowly through the critical range on the cooling bed by piling one plate on top of another, or by piling and covering with sand.

The Manufacture of Acid Open-Hearth Steel for Forging Ingots. H. P. Rassbach. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Feb., pp. 289-302). An outline is given of acid open-hearth practice for the production of ingots for heavy forgings at the plant of the Midvale Steel Co., Philadelphia. The furnaces used vary in capacity from 50 to 70 tons and are oil-fired. Fundamental slag reactions are discussed. The sizes of the ingot moulds used range from a 9-in. sq. to a 108-in. octagon. The lightest ingot poured is 600 lb. and the heaviest is 500,000 lb. Four methods of pouring are practised: (1) Bottom-pouring through a runner; (2) top-pouring direct into the mould; (3) top-pouring through a head box; and (4) combination of top and bottom pouring. In pouring an ingot from the bottom entirely there is a tendency for the formation of pipes and secondary shrinkage cavities. However, by pouring only the body of the ingot from the bottom and then filling up the sinkhead from the top, this condition can be eliminated.

Deoxidation of Steel with Silicon. C. H. Herty, jun., and G. R. Fitterer. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Apr., pp. 569-588). The authors present an outline of the function of silicon in basic open-hearth practice, and the results of an investigation on the mechanism of the deoxidation of steel with silicon. The formation and elimination of silicates are briefly discussed. It is concluded that the mechanism of deoxidation with silicon is, first, the formation of silica by the reversible reaction of silicon with FeO, and, secondly, a fluxing of more FeO by the silica, forming a ferrous silicate inclusion. Complete deoxidation of steel is impossible unless the oxide formed is absolutely infusible and insoluble at steel-making temperatures. It is also concluded that silicates high in iron or manganese will be more readily eliminated from the bath than high silica particles, due to their lower melting point, with consequent increased rate of coalescence.

Ferrous Silicates in Steel. C. H. Herty, jun., and G. R. Fitterer. (Proceedings of the American Society for Testing Materials, 1928, Vol. 28, Part II., pp. 23-40). The results are reported of an investigation on deoxidation with silicon, with particular emphasis on the type of inclusion formed when various amounts of silicon are added to a bath of steel, and on the effect of the silicates on the forging and rolling of steel.

The System Ferrous Oxide-Silica. C. H. Herty, jun., and G. R. Fitterer. (Industrial and Engineering Chemistry, 1929, Vol. 21,

Jan., pp. 51-57). The authors present the results of a study of the equilibrium diagram of the system FeO-SiO_2 , wherein the melting points of slags low in silica are dealt with. A comprehensive survey of all previous work on the system is given and compared with the present work. The methods used in the preparation of the ferrous silicates, the micro-analyses, and the determinations of melting points are different from those used in any previous investigation on this system. A complete equilibrium diagram has been constructed, and is represented in a three-dimensional figure by plotting composition against temperature against heat content.

Unreduced Oxides in Pig Iron and their Elimination in the Basic Open-Hearth Furnace. C. H. Herty, jun., and J. N. Gaines, jun. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 165). Much trouble has been experienced by steelmakers in making good steel from a type of iron known generally as "bad iron" or "dirty iron," although within the specified limits as to ordinary analysis. Among the reasons suggested is that unreduced material in the iron is responsible. This problem has been investigated and the results are presented. Inasmuch as a "spell" of dirty iron occurs without warning and may be of short duration, it was deemed advisable to attempt to simulate the conditions existing before and during such a period and compare the quality of the steel made with the normal and with the dirty iron. Three heats were observed, using iron made under normal operating conditions at the blast-furnace. The burden was then increased to throw the furnace on the cold side, and two open-hearth heats were made from the resultant low-silicon, cold-hearth iron. The operation of the blast-furnace and open-hearth was followed closely, a large number of samples, temperature readings, and other data being taken. The open-hearth product, a low-carbon rimming steel, was rolled into 4×4 -in. billets, then to $1\frac{1}{2}$ -in. rounds; some of the billets were rolled into sheets and were zinc-coated.

It can be stated from the results that there is generally a certain quantity of oxides, chiefly SiO_2 , FeO , MnO , and Al_2O_3 , in pig iron from the blast-furnace. The total amount varied in this test from a trace to about 0.13 per cent. of the weight of the iron. It is shown that the highest percentages of silicates (this term is used to indicate the total non-metallic impurity, since SiO_2 is the main constituent) are met with at times when the furnace is working irregularly. A comparatively rapid change in hearth temperature, whether hotter or colder, or an increase in the rate of stock descent, such as a slip, will cause a sharp increase in the silicate content of the iron.

In the open-hearth the iron used during the five heats varied in its silicon content from 1.11 to 0.20 per cent. As would be expected, the heats with the low-silicon iron melted soft and offered some difficulty in working and in forming the slag; however, no noticeable difference in the quality of the finished steel could be detected. Bars from the heats were rolled into sheet and were zinc-coated, with no

difference in quality between heats. It should be kept in mind that low-carbon rimming steel heats were made in this investigation in order to avoid complications arising from the introduction of silicon in higher carbon heats.

Tables and curves showing logs of the various heats are given. In none of the test heats was the steel sufficiently dirty to show defects which could be traced to silicates from the pig iron, and the data collected are not sufficient to correlate bad iron with trouble in the finished steel.

Oxygen Contents in Basic Open-Hearth Steel before the Addition of Deoxidisers. A. Silin. (Journal of the Russian Metallurgical Society, 1929, No. 1, pp. 102-112). (In Russian.)

A Study of Sulphur in the Basic Process. H. L. Geiger. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 287-289). The author continues his discussion of sulphur in the basic open-hearth process (see Journ. I. and S.I., 1928, No. II. p. 299). In the present article the sources of sulphur, especially the fuel, are outlined, and methods of desulphurisation are briefly reviewed.

The Comparative Economy of Various Decarburisers used in the Open-Hearth Process. S. Schleicher. (Stahl und Eisen, 1929, Vol. 49, Apr. 4, pp. 458-462). Trials were made in an open-hearth furnace with various decarburisers with the object of discovering the effect of these on the cost of the process. Rolling-mill scale proves to be the most economical, the value of the iron gained being slightly in excess of the cost of the scale and lime added. With pure Swedish ore, after balancing gains and losses, the cost works out at 2.46s. per 100 kg. of carbon requiring to be burned. Using siliceous hematite (with Fe_2O_3 57.71, and SiO_2 40.80 per cent.) the cost becomes 10.84s. per 100 kg. of carbon burned, the reason for the much higher cost being the increased quantity of lime added and the higher loss of iron by burning. The quantity of oxygen in the decarburiser does not in the least affect the speed of decarburisation, but it does determine the amount of decarburiser required. The decarburiser should be added in a quantity corresponding to the rate of combustion of the carbon in the bath. If added in excess of that rate, the excess iron of the ore used is slagged, instead of going into the bath.

Conditions on which the Effects of Decarburising Agents Depend in the Open-Hearth Furnace. E. Killing. (Stahl und Eisen, 1929, Vol. 49, Apr. 18, pp. 527-531). The comparative value of various ores used as decarburisers is again studied. The chief factors to consider in choosing a decarburiser are the iron content, the quantity and form of combination of the oxygen, the degree of acidity or basicity, the amount of injurious constituents, the mechanical condition, and

the moisture free or combined. The effect of the decarburiser is mainly influenced by the time at which it is added, the bath temperature, the composition of the charge and of the slag, the composition of the gas and quantity of air for combustion, and the hearth area. The kind of ore chosen may have quite an appreciable effect on the cost of production. The theoretical calculations concerning the advantage of ferric oxide as compared with ferrous have proved true in practice. A high silica content in a decarburiser greatly reduces its efficiency.

Significance of the Simple Steel Analysis. H. D. Hibbard. (Transactions of the American Institute of Mining and Metallurgical Engineers, 1928, Vol. 76, pp. 666-688). The author points out the limitations of ultimate analysis as an indication of the properties of a simple steel, and describes the functions of the different constituents in steel-making practice.

Basic Open-Hearth Yields. C. D. King. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 186). In discussing basic open-hearth yields the author refers to the ingot yields obtained in the process of converting pig iron, scrap, and ore to steel. In this conversion some scrap is produced. The difference between the total weight of ingots and scrap produced and the original metallic charge constitutes the loss. Basic open-hearth yields vary considerably, and while some of the divergencies can be explained metallurgically because of differences in slag analysis, proportion of pig charges, and character of steel made, there often remain differences that apparently do not readily disclose themselves.

The losses in basic open-hearth practice are usually as follows: carbon eliminated with waste gases; metalloids elimination in slag; free Fe in slag; unrecoverable spillage; metallics lost and lodged in checker chamber dust, brickwork, and slag pockets, and carried away by waste gases; and wastage incidental to recovery and preparation of miscellaneous scrap. If the condemned ingots and ingot butts are added to this group and provision is made for loss on "additions," this grand total subtracted from the gross metallic mixture gives the ingot yield. The influence of the various types of losses and the method of calculation are explained in detail. Duplex practice is also considered.

The Measurement of Gas Temperatures up to 1500° in Radiation Fields of Varying Anisotropy. H. Schmidt. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 293-298). In order to carry out a complete study of the temperature of the gases in all parts of an open-hearth furnace, and at all points in their flow through the furnace and regenerators, it is necessary to be able to register gas temperatures of over 1500° C. Accordingly, a gas pyrometer of improved construction has been devised. The thermo-element is a platinum/

platinum-rhodium couple enclosed for better protection in a water-cooled platinum-rhodium tube. An illustration of the arrangement is shown, and a description of the *modus operandi* is given. One difficulty is the recording of rapid variations in the gas temperatures, and this difficulty is more successfully overcome with the water-cooled thermo-element than with the ordinary pyrometer, as shown by comparative records taken with the new type and the old type of apparatus.

Ladle Changes in Constituents of Steel and Slag. (Iron Age, 1929, Vol. 123, Apr. 11, p. 1020). Slag action in a ladle of steel from the open-hearth furnace was a subject of a discussion by C. H. Hertý, jun., at a recent meeting of the American Institute of Mining and Metallurgical Engineers. Two diagrams are published which were referred to in the discussion; one of these shows the changes in the concentration of metalloids in the steel beginning 3 min. after the start of tapping the heat from the furnace, and running up to the 28th ingot teemed from the heat 46 min. later. This diagram shows the sharp reduction in the proportion of manganese as the last few ingots were reached. In the other diagram is found a similar history of the concentration of slag constituents. Most pronounced among the changes is the rapid increase in silicon from the time the heat was tapped until about 15 ingots had been poured. After this the silica content was about stationary. At the same time there was a considerable drop in iron oxide during the first portion of the period, and then, after a time of stability, a further drop following the 16th ingot.

Influence of Different Kinds of Scrap on the Working Conditions and Economy of the Open-Hearth Process. E. Kerl. (Stahl und Eisen, 1929, Vol. 49, Jan. 3, pp. 1-7). In Germany more than one-half of the total output of steel is made from scrap, and trials have been carried out with a view to discovering the effect of the different classes of scrap on the conditions of working and economy of the open-hearth. The trials were made at the Höntrop works of the Vereinigte Stahlwerke A.G., two tilting furnaces of 120-ton capacity being used for the purpose. The furnaces were fired with a mixture of coke-oven and blast-furnace gas, mixed in the proportion of 1 to 1.85, the minimum heat value of the mixture being 2060 kg. cal. per cu. m. In furnace No. 1, 5 heats were made with good cold ingot crop ends, 8 were made with bundled clean sheet-iron scrap, and 5 with light detinned scrap in bundles. In furnace No. 2, 3 heats were made with crop ends of ingots, 3 were made with detinned bundled scrap, 2 with clean steel turnings, 2 with rusty steel turnings, and 8 with imported steel scrap. The pig iron was a high-manganese pig (Stahleisen) with 3.77 per cent. of manganese, and was for the most part charged liquid. The scrap was all mild steel containing carbon 0.08 and manganese 0.4 per cent., except the turnings, which had carbon 0.25 and manganese

0.68 per cent. The end product was a desiliconised steel for sheets with a tensile strength of 26 to 31 tons per sq. in. The table below shows the main results, the fuel consumption being calculated as the equivalent of an ordinary coal with a calorific value of 7000 kg. cal.

The temperature of the liquid pig charged was from 1220° to 1230° C.; the temperature of the steel on tapping was 1520° to 1580°, the first ladle being generally cooler than the second. The teeming temperature measured on the stream of molten metal was 1480° max. and 1420° min. A number of other data concerning pressure and composition of waste gases are given. The results of the trials show the limitations when using only one of several kinds of scrap, but in practice this never occurs, as the scrap kinds are invariably mixed, but they indicate the disadvantages of working with heavy cold scrap alone.

Material Charged.	Ingot Crop Ends.	Light Bundled Scrap.	Detinned Sheet Scrap.	Clean Steel Turnings.	Rusty Turnings.	Imported Scrap.
Average total weight of metal charged, tons	78.34%	68.68%	55.26%	74.40%	77.04%	70.68%
Proportion of charge in kg. per ton of good ingots obtained:	125.25	133.5	138.7	133.5	136.7	125.5
(a) Scrap kg.	833.7	750.1	629.2	829.4	866.0	754.8
(b) Liquid pig "	217.6	326.0	467.6	234.7	217.0	291.0
(c) Solid pig "	6.8	15.6	22.0	15.0	21.9	6.8
(d) Swedish ore (68% Fe) "	6.4	2.8	12.7	29.4	13.8	6.4
(e) Ferro-Mn (73.5% Mn) "	3.4	4.4	5.8	5.6	3.8	4.8
(f) Aluminium . . . . "	...	...	...	...	...	0.05
Total kg.	1067.9	1098.9	1137.3	1114.1	1122.5	1063.85
Yield of ingots in % of metal charged	93.58	90.94	87.87	89.79	88.97	93.0
Loss % of metal charged . .	4.24	6.38	9.64	7.37	9.26	4.54
Fuel consumption, expressed as coal, per ton of steel . kg.	149.5	143.6	151.4	164.5	187.0	146.2
Lime " " . "	14.75	16.30	31.50	33.70	39.65	15.0
Dolomite " " . "	16.65	16.65	16.65	16.65	16.65	16.65

Scrap Consumption is Growing. C. E. Wright. (Iron Age, 1929, Vol. 123, Feb. 7, pp. 411-412). A review of the scrap situation in the American iron industry. During the last five years the total amount of steel ingots produced was 40,000,000 tons in excess of the pig iron output. Steel production is increasing at an annual rate of 1,000,000 tons, whereas the annual increase in pig iron output has been averaging 423,000 tons.

How Use of Scrap is Increasing. C. H. Strand. (Iron Age, 1929, Vol. 123, Feb. 14, pp. 471-474). Tabulated information is given

showing the scrap production and consumption in the different districts of the United States. It is estimated that in 1928 34,000,000 tons of scrap were consumed, half of which was used in plants where it was produced, the other half being obtained on the market.

Cards for Recording Open-Hearth Furnace Operations, Repairs, and Working Costs. F. Lüth. (Stahl und Eisen, 1929, Vol. 49, Feb. 14, pp. 209-212). A scheme for keeping all steel furnace records on cards is outlined. A set of four cards designed for different kinds of records is illustrated: (1) for recording the metallurgical operations of each heat; (2) for recording the weekly production of ingots, consumption of fuel, and costs; (3) for monthly records of repairs and their costs; and (4) for noting all data regarding design and dimensions of the furnace and accessories, and any alterations made during the lifetime of the furnace.

The Utility of the Graphic Representation of Costs of Production. C. E. Schulz. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 341-353). The article presents a graphic comparison of the costs of production per ton with and without taking account of the degree of employment, a comparison of monthly costs, a consideration of the factors which influence the amount of the costs, and the dependence of the costs on the degree of employment. Finally, the practical application of graphic methods is discussed, examples being given.

The Electric Melting Furnace in the Iron and Metal Industry. E. Häuser. (Zeitschrift des Oesterreichischen Ingenieur- und Architekten-Vereines, 1928, Vol. 80, Sept. 28, pp. 375-378; Oct. 12, pp. 392-395).

The Present Status of the Electric Furnace. W. Schreck. (Giesserei Zeitung, 1929, Vol. 26, Jan. 15, pp. 29-36). A general discussion of the electric furnace, its lining, the refining of iron, the melting-down of turnings, and the calculation of costs.

Progress of Electric Furnaces. W. S. Gifford. (Paper read before the Sheffield Branch of the Institute of Metals: Foundry Trade Journal, 1929, Vol. 40, Apr. 25, pp. 311-312).

Electric Melting of Alloy Steels. H. M. German. (Iron and Steel Engineer, 1928, Vol. 5, Dec., pp. 507-510; Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., 274-276). A general discussion of the problems involved in the manufacture of alloy steels in the electric furnace.

Manganese Steel Production in the Electrical Furnace. J. Trantin, jun. (Foundry, 1929, Vol. 57, Jan. 1, pp. 15-19; Jan. 15, pp. 52-55;

Feb. 1, pp. 128-131). The author describes the principles underlying the melting of manganese steel in the electric furnace. The heat treatment of manganese steel is dealt with, and the results of a number of investigations are presented to show the effect of treatment at different temperatures. The author also deals with the effect of secondary heating, such as occurs in shrinking shells on rolls, of welding, and of forging on the microstructure and physical properties.

Economic Considerations in the Choice and Working of Electric Resistance Furnaces. V. Paschkis. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Feb., pp. 487-494). The costs of treating materials in various types of electric resistance furnaces are analysed and compared, and the practice to be adopted for securing the best efficiency is indicated.

Dimensions, Operating Conditions, and Efficiencies of German Electric Steel Furnaces. S. Kriz. (*Stahl und Eisen*, 1929, Vol. 49, Mar. 28, pp. 417-425). Data are given concerning the construction, working, and output of 56 arc furnaces and 13 induction furnaces. The particulars were obtained by means of a questionnaire addressed to users of electric steel furnaces in Germany, and the returns afford evidence, if any were still required, that the advantages of the arc furnace, as compared with the induction furnace, are now definitely established. The number and types of arc furnaces described are 42 Héroult, 7 Nathusius, 6 Stassano, and 1 Girod, and the data relate to electric conditions, weight of charge, design of furnace and materials of construction, and power consumption. Similar data are recorded for 12 Röchling-Rodenhauser induction furnaces and for 1 of the Frick type.

The Electric Furnace in the Different Plants of the Société des Aciéries Firminy. R. Sevin. (*Journal du Four Électrique*, 1928, Vol. 37, Nov., pp. 335-337).

Electric Induction Furnaces of the Russ Type. (*Journal du Four Électrique*, 1928, Vol. 37, Dec., pp. 369-374). A comparison is made of large and small induction furnaces, and their advantages and operation are discussed.

The "Metrovick" Coreless Induction Furnace. (*Iron and Coal Trades Review*, 1929, Vol. 118, Mar. 8, pp. 362-363). Illustrated particulars are given of the constructional details of the "Metrovick" furnace. It consists of a water-cooled inductor coil mounted on a wooden box, supported on trunnions of non-magnetic cast iron, and tilted by an electric motor on an axis about the lip of the crucible. Hand-operated tilting gear is also provided. The crucible is directly lagged into the inductor with ganister or zircon sand supported on a

concrete block, the whole being surrounded by a wood casing. The inductor coil is made of heavy section copper bar wound on edge, and fitted with water-cooling pipes, which are isolated from the molten metal by a thick wall of copper in addition to the lagging of sand. The completed coil is suitably insulated, and finally heated under pressure, thus forming in effect a thick copper cylinder, which surrounds the crucible and can readily be clamped in position. The supply leads are taken to a switch at the bottom of the box, the switch being connected to the ends of the coil and also to a tapping, thus making it possible to employ the whole or part of the coil, and so regulate the power supply of the furnace. A furnace of 350-lb. capacity is at work in the experimental foundry of the Metropolitan-Vickers Research Department, and another of 5-cwt. capacity is in operation at the Sheffield works of Vickers-Armstrongs, Ltd.

Progress in the Construction of High-Frequency Furnaces. M. Tama. (Stahl und Eisen, 1929, Vol. 49, Apr. 11, pp. 499-502). An illustrated description is given of a new high-frequency furnace. The furnace is of the coreless induction type with an iron yoke. The principles of high-frequency heating are discussed.

High-Frequency Induction Furnaces. (Metallurgist, 1928, Vol. 4, Nov. 30, pp. 170-171). An abstract of an article by M. H. Kraemer (Stahl und Eisen, 1928, Vol. 48, Aug. 16, pp. 1120-1124 : *see* Journ. I. and S.I., 1928, No. II. p. 333).

Melting Steel in the High-Frequency Furnace. H. Neuhauss. (Foundry, 1929, Vol. 57, Feb. 15, pp. 146-150 ; Mar. 1, pp. 192-194, 218). The author discusses the high-frequency electric furnace as a melting unit for the production of steel, and describes the operations involved in melting and refining certain types of steel, including stainless steel. Figures are also given showing the power consumption for producing stainless steel, and some data on the possibilities of this type of furnace in connection with a cupola melting an all-steel scrap charge as a duplexing unit for steel foundries.

Selection of Electrical Equipment for Arc Furnaces Used in the Melting and Refining of Metals. S. Arnold. (Iron and Steel Engineer, 1929, Vol. 6, Feb., pp. 75-78).

Sponge Iron : A Raw Material for Electric Steel. N. K. G. Tholand. (Paper read before the American Electrochemical Society, May 1929). The value of sponge iron as a substitute for scrap in electric steel-making practice is pointed out. The properties of Höganäs sponge iron are outlined, and typical furnace charges using the Höganäs product, and analyses of the steels are tabulated. The properties of steels made with German sponge iron are also given.

SLAGS.

Microscopic Constitution and Structure of Various Treated Basic Slags, and their Relation to the Citric Acid Solubility. H. Schneiderhöhn. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 213-223). Ordinary Thomas slags, with and without silicic acid additions, were examined after cooling under various conditions. The constituents were shown to be in equilibrium. The various constituents were distinguished by the analysis of the citric-acid-soluble portion of the slags. The difference of solubility of the slags with and without silicic acid additions was attributed to the presence of lime compounds in the samples without additions which suppressed the solubility of the silico-carnotite; the dissimilar ions going into solution from the samples with additions increased the solubility of the silico-carnotite. It is stated that earlier methods of estimating the so-called free lime in basic slags are valueless. Decomposition effects were studied, and the phenomena were attributed to hydration and "carbonisation" of the crystallised lime.

STEEL PLANTS.

The Algoma Steelworks and Railways, Ontario. (Engineer, 1928, Vol. 146, Nov. 2, pp. 488, 494). The plans of the Lake Superior Corporation for the future expansion of its plants in the Algoma district of Ontario, Canada, are outlined, and brief details of the Algoma Steel Company, its principal subsidiary, are given.

The Jamshedpur Iron and Steel Works. (Engineer, 1928, Vol. 146, Nov. 23, pp. 572-574, 576). An illustrated description of the plant and operation of the Jamshedpur works of the Tata Iron and Steel Co., Ltd.

Timken Steel and Tube Company Plant. C. Longenecker. (Blast-Furnace and Steel Plant, 1929, Vol. 17, May, pp. 698-715). A complete illustrated account is given of the layout and equipment of the steel plant of the Timken Steel and Tube Co., Canton, Ohio. The melting equipment consists of three 100-ton open-hearth furnaces, one 7-ton, two 25-ton, and one 50-ton Héroult electric furnaces. While the rated capacity of the open-hearth furnaces is 100 tons the average charge is 220,000 lb., made up of approximately 55 per cent. of selected scrap, 10 per cent. of limestone, and the balance pig iron. The rolling-mill equipment consists of a 35-in. blooming mill, a 28-in. mill, a 22-in. mill, a rod mill, a 36-in. seamless tube mill, and 10-in. and 12-in. merchant mills.

Plant of the Gulf States Steel Company. C. Longenecker. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 147-161). A detailed description of the company's works at Alabama City, together with notes on the raw materials used and the operation of the plant, is given.

STEELWORKS MACHINERY.

Lifting Magnets : Early History. F. W. Jessop. (Iron and Steel Engineer, 1929, Vol. 6, Jan., pp. 11-14). The development of lifting magnets for handling materials in a steelworks is outlined.

Electric Lifting Magnets. J. A. Smeeton. (Iron and Steel Industry, 1929, Vol. 2, Mar., pp. 171-172). Recent developments in the design and use of electric lifting magnets are discussed.

The Determination of the Moment of Rotation (Tilting) of a Ladle. H. König. (Die Giesserei, 1929, Vol. 16, Mar. 22, pp. 261-265). The method of determining the moment of rotation of a ladle about its trunnions is described.

Locomotive for Steel Mill Service. (Blast-Furnace and Steel Plant, 1929, Vol. 17, May, pp. 723-724). A 35-ton "gasoline-electric" locomotive for use in steelworks is described.

CASTING AND TREATMENT OF INGOTS.

Third Report on the Heterogeneity of Steel Ingots. (Presented to the Iron and Steel Institute, May 1929 : this Journal, p. 305).

A New Method for the Production of Sound Steel. Sir Charles Parsons and H. M. Duncan. (Paper read before the Iron and Steel Institute, May 1929 : this Journal, p. 255).

Heat Equilibrium between Ingot and Ingot-Mould Wall. B. Matuschka. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Jan., pp. 405-411). In the process of the solidification of steel ingots the conditions of first importance are those which influence the mode of freezing and the formation of the primary crystalline structure. These conditions mainly consist in the shape and dimensions of the mould and head, the initial temperature of the steel, the ratio of the heat content of the ingot to that of the mould, the chemical composition of the steel and its fluidity, the speed and method of pouring. The

transmission of heat from the ingot to the atmosphere through the mould wall proceeds in two stages: the establishment of a heat equilibrium between the ingot and the mould walls, and the dissipation of the heat of the mould walls into the air. The author describes experiments to determine the rate at which heat passes from the ingot to the mould and from the mould to the air. The mould used was circular in section, being 10 in. in diam. at the upper end of the chill and $8\frac{3}{4}$ in. at the bottom, the length of the chill being about 40 in. with walls $3\frac{3}{8}$ in. thick. The weights were, for the mould 610 kg., the head 85 kg., and the ingot 340 kg. The successive casts consisted of a tool steel with carbon 0.65 per cent., two chrome-nickel steels, a high-speed steel, and a rustless steel with 0.2 per cent. carbon and 12 per cent. chromium. At a distance of 10 in. from the upper edge of the mould two holes were bored, perpendicular to the axis. One was bored right through the mould wall and then plugged on the inside with a cast-iron plug 5 mm. long; the second was bored to a depth of 5 mm. in the wall, and the two holes were 3 in. apart circumferentially. A platinum/platinum-rhodium element was inserted in each hole. The 0.65 per cent. carbon steel was cast at a temperature of 1550°C . At the point 5 mm. from the inner face of the mould the temperature ran up instantaneously to 580°C ., but 60 sec. elapsed before the temperature began to rise at the point 80 mm. from the inner face. In 20 min. the inner part of the wall had risen to a maximum of 650° . A second ingot of the same steel was upset after 60 sec., and it was found that the chilled shell of the ingot had attained a thickness of 1 to $1\frac{1}{8}$ in. by that time. The flow of heat into the mould walls is very soon checked by the parting of the ingot from the mould as it shrinks in cooling. To determine the time from the moment of filling the mould till parting occurred, two cast-iron plugs were inserted at opposite sides of the mould and insulated from it, the inner ends being made flush with the inner face of the mould; leads were taken from these plugs to a battery and a bell was placed in the circuit. The plugs were fixed 10 in. below the top edge of the mould. As soon as the liquid steel reached the plug the circuit was made and the bell sounded until the parting of the chilled surface of the ingot from the mould wall occurred, thus breaking the circuit again. It was found that the time varied from 1 min. 25 sec. for the 0.65 carbon steel, to 1 min. 40 sec. for chrome-nickel steel, 4 min. 30 sec. for an 0.80 carbon tool steel, 2 min. 58 sec. for a high-speed steel, and 2 min. 50 sec. for a 12 per cent. chromium steel. Those steels which remain longer in contact with the mould solidify considerably quicker than the others, and show in the outer zone a dull fracture with fine or medium-fine crystalline structure. Those which part quickly from the mould might be expected to show a coarse crystalline structure in the outer zone, but on the contrary they show a very fine structure, and this discrepancy the authors are unable to explain. The flow of heat and time-temperature distribution of the heat through the mould walls are very clearly set out in diagrams.

Contraction and Piping during the Solidification of Metallic Melts.

H. Obermüller. (Giesserei Zeitung, 1929, Vol. 26, Jan. 15, pp. 41-44). The process of solidification of pure metals, eutectics, and solid solutions are described. The connection between contraction and piping and the freezing process is explained.

Some Notes on the Coalescence of Non-Metallic Inclusions in Steel.

C. H. Herty, jun. (Proceedings of the Engineers' Society of Western Pennsylvania, 1928, Vol. 44, Nov., pp. 259-267).

Why Ingot Moulds have Short Life. J. H. Hruska. (Iron Age, 1929, Vol. 123, Feb. 21, pp. 539-541). The author has studied the chemical and physical changes occurring in ingot mould walls during the life of the mould. Large graphite flakes offer a decreased resistance toward intercellular cracks, thermal fatigue, and oxidation of the mould metal, thus decreasing the number of heats per mould. The beneficial influence of an increase in the surface hardness of moulds is pointed out.

FORGING AND ROLLING-MILL PRACTICE.

REHEATING FURNACES.

Reheating Furnaces for Alloy Blooms. (Iron Age, 1928, Vol. 122, Dec. 27, pp. 1632-1634). **Continuous Furnaces for Alloy Blooms.** A. K. West. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 124-126). The two continuous reheating furnaces provided for the new mill of the Timken Steel and Tube Co., Canton, Ohio, are described and illustrated. The furnaces are of the triple-fired recuperative type, using natural gas and having a capacity of 40 tons per hr. each. The blooms are pushed through the furnaces by means of a motor-driven mechanism. Upon entering the furnaces the blooms are gradually warmed in a 10-ft. dead end, next passing through the channel and main heating chamber, and lastly receiving their final soaking at a temperature of approximately 2200° F. on a brick hearth, whence they are discharged by gravity on to a run-out table. There are three tiers of burners, one located at the discharge end for maintaining the soaking chamber at the desired temperature, and the other two behind the soaking hearth, one firing above the blooms near the roof of the main heating chamber and one below the level of the hearth firing beneath the blooms. The preheated air is delivered to both the main heating chamber tiers of burners under positive pressure by the refractory tile recuperator, which is situated beneath the furnace proper and is arranged in three units. The central recuperator unit furnishes its preheated air to the under-fired burners; the two outside recuperators deliver preheated air to the overhead firing ports by means of two steel ducts which are insulated and brick-lined.

Development of the Continuous Pack-Heating Furnace. J. A. Hunter. (Proceedings of the Engineers' Society of Western Pennsylvania, 1929, Vol. 45, Feb., pp. 1-9). The author describes a continuous gas-fired furnace for heating sheet packs of fours and eights. The original furnace was 30 ft. long and 42 in. wide inside the brickwork. The hearth consisted of revolving discs made of steel containing 18 per cent. of chromium; eight gas burners were fitted, four at each end of the furnace, two being above and two below the discs. The burners were not satisfactory owing to the deposition of soot and tar on the packs, and a burner of the Venturi type was substituted. Due to the high velocity of the gases leaving the burner there was a tendency for the gases to carry to the end of the combustion chamber. To overcome

this and to obtain proper distribution of the gases in the heating chamber, the opening between the combustion chamber and the heating chamber was made larger at the burner end and progressively smaller to the other end. With this arrangement proper furnace conditions were obtained, but the furnace did not have sufficient capacity to heat both the fours and eights satisfactorily at the required rate. When the furnace was forced to heat the cold fours, the eights were too hot, and to prevent the eights being overheated the length of the furnace was increased to 38 ft. Subsequently a preheater was fitted to the furnace. The cold air entered near the top of the preheater, and after making three passes was delivered to the burners at a temperature of 500° to 550° F. The fuel used was raw producer-gas, and the high sulphur content is believed to have caused failure of some of the alloy steel discs and shafts. These had to be replaced after about 7 months' operation with discs and shafts of chrome-nickel steel.

Electric or Fuel-Fired Furnaces for Tube Works? H. Sack. (*Röhrenindustrie*, 1929, Vol. 22, Jan. 31, pp. 35-36). The author discusses the relative merits of electricity and fuel-firing for the heating of furnaces for the drawing of tubes.

Forge Heating for Large Pieces. J. R. Miller. (*Heat Treating and Forging*, 1929, Vol. 15, Feb., pp. 219-220).

FORGING, STAMPING, AND DRAWING.

Principles of Machine Forging. H. Kilborn. (*Iron Age*, 1929, Vol. 123, Apr. 11, pp. 1003-1005; Apr. 25, pp. 1151-1152). A series of articles dealing with machine forging. The first article considers the apparatus used and includes a brief history of drop-forging. The second article deals with the design of dies.

Horizontal Forging Machines. H. Fey. (*Stahl und Eisen*, 1929, Vol. 49, Mar. 7, pp. 315-324). Illustrated descriptions are given of various types of horizontal forging machines, showing details of their mechanism. A number of pieces of a great variety of shapes forged by such machines are also illustrated.

Forging Machine for Repetition Work. (*Engineer*, 1928, Vol. 146, Nov. 16, p. 556). The application of the electrically operated forging machine built by Messrs. B. and S. Massey, Ltd., for the manufacture of motor-car axle "uses" is described. A test of 19 min. duration, in which 7 complete axle "uses" were made, demonstrated that the current consumption was at the rate of half a unit per axle.

Drop-Forgings and Machine Forgings. F. W. Spencer. (Metal Industry, 1928, Vol. 33, Nov. 30, pp. 517-518).

Year's Progress in Drop-Forge Equipment. M. S. Reed. (Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 42-43). The advances made in the design of hammers and presses are outlined.

Producing an Unusual Drop-Forging. W. Hopson. (Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 60-61). The special feature of the drop-forging described was that it was required to have sharp curved teeth of even height so that they could make uniform contact with a 6-in. pipe.

Preparation of Steel for Drop-Forgings. J. R. Miller. (Heat Treating and Forging, 1929, Vol. 15, Mar., pp. 311-312). The author enumerates some of the points to which drop-forgers give special attention when accepting billets (central soundness, good surface, close analysis, &c.), and reviews the methods adopted by the steel-maker to meet these requirements.

The Manufacture of Die Blocks. J. A. Succop. (Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 51-54). Open-hearth furnace, forging, and heat-treating practice for the production of die blocks is outlined.

Calculation of the Specific and Absolute Steam Consumption of Hammers in the Forging Down of Alloy Steels. O. Niederhoff. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Mar., pp. 545-556). A large amount of work was carried out to determine the specific resistance to deformation at different temperatures of carbon steels, chromium steels, tungsten steels, and nickel, manganese, manganese-silicon, chromium-tungsten, nickel-chromium, and high-speed steels. At 1100° to 1200° C. there is little difference in the resistances, but, as may be expected, the values of resistance to deformation, expressed in kg.-mm. per cu. mm., vary considerably as the temperature falls, according to the percentage of carbon or other alloying element. The steam consumption in a 10-cwt. hammer appears to range from 40 gm. of steam per blow to produce a displacement of 10 cu. cm. of material, up to 220 gm. to produce a displacement of 20 cu. cm.

Safe Stress Limits for Forged Steel. J. W. Urquhart. (Heat Treating and Forging, 1928, Vol. 14, Nov., pp. 1282-1284). A number of failures of machine parts in practice are mentioned; the question of the safety factor is shown to involve a thorough knowledge of both the manufacturing methods to be employed and the service conditions to be encountered.

Metallurgical Problems of Large Turbo-Generator Design. J. A. Kuyser. (Paper read before the Institution of Electrical Engineers, Mar. 21, 1929: *Iron and Coal Trades Review*, 1929, Vol. 118, Mar. 29, pp. 463-464). Important advances have been made in the production of high-class rotor forgings. The material generally used before the introduction of large 3000 r.p.m. sets was a carbon steel having a low nickel content, the physical properties of which were as follows: Ultimate tensile strength, 36 tons per sq. in.; yield point, 20.5 tons per sq. in.; elongation on 2 in., 20 to 24 per cent.; reduction of area, 30 per cent. For more severe duties a steel has been developed which meets the following specification: Ultimate tensile strength, 42 tons per sq. in.; yield point, 24 tons per sq. in.; elongation on 2 in., 16 to 20 per cent.; reduction of area, 28 per cent. This steel contains about 2 per cent. of nickel and a very small percentage of chromium. Builders of generators on the Continent have for some time been using oil-hardened chromium-nickel steel forgings having a nickel content of 3 to 4 per cent. and a chromium content of 0.7 to 1.0 per cent. These forgings are heated and quenched to obtain a yield point of 32 to 34 tons per sq. in., and an ultimate strength of 45 to 48 tons per sq. in. The author's experience has shown the effect of oil-hardening in setting up dangerous strains in these forgings, rendering it advisable to adhere to the old practice of using annealed forgings only.

Normalised Vanadium Steel Crankshafts. W. J. Learmouth and J. H. Abbott. (*Heat Treating and Forging*, 1929, Vol. 15, Jan., pp. 99-100). The Studebaker Corporation's forge heating and final treatment for crankshafts are described. The use of vanadium steel simplifies the forging operations and avoids the need for quenching. The analysis of the steel is: Carbon, 0.44 to 0.49; manganese, 0.65 to 0.85; sulphur, max. 0.05; phosphorus, max. 0.04; vanadium, 0.12 to 0.20 per cent. The carbon is kept within the range specified in order that excessive rejections for hardness may not occur; after being normalised at 1650° F. and cooled in air the minimum physical properties of the metal are: Yield point, 65,000 lb. per sq. in.; ultimate strength, 100,000 lb. per sq. in.; elongation on 2 in., 18 per cent.; reduction of area, 45 per cent.; and Brinell hardness number 196.

Forging Drill Stems from S.A.E. 1035 Steel in Hydraulic Press. G. E. Merkley. (Paper read before the Western Metal Congress, Jan. 1929: *Iron Trade Review*, 1929, Vol. 84, Feb. 21, pp. 524-525). An outline is given of the manufacture of rotary drill stems for oil wells. The stems are formed from billets in hydraulic presses. The machining of the stems is unique in that the principal operation requires a watercourse hole to be drilled through the centre for the entire length of the stem, which is 51 ft. in the longer sizes. This operation is performed in lathes equipped with a special headstock, tool chuck, feed-screw, and holding fixture.

Bolt-Making by the Hot-Forging and Cold-Pressing Methods. E. J. Wiley. (Drop-Forger, 1929, Vol. 9, May, pp. 46-72).

Modernised Plant for Making Hot Pressed Nuts. G. A. Richardson. (Iron Trade Review, 1928, Vol. 83, Nov. 1, pp. 1119-1122). **New Equipment Speeds Output of Track Bolts, Nuts, and Spikes.** G. A. Richardson. (Iron Trade Review, 1928, Vol. 83, Nov. 8, pp. 1175-1178). The continuation of a series of articles describing mass production methods employed in the manufacture of bolts and nuts at the plant of the Bethlehem Steel Co. (See Journ. I. and S.I., 1928, No. II. p. 375.)

The Forging of Drums for very High-Pressure Boilers. C. Dantin. (Génie Civil, 1929, Vol. 94, Jan. 26, pp. 77-81). The author describes and illustrates the methods of manufacture employed at Messrs. Vickers-Armstrongs, Ltd. (Sheffield), and at the Midvale Co. (Philadelphia).

Weldless Steel Drums for High-Pressure Boilers. (Engineering, 1928, Vol. 126, Nov. 30, p. 676, and 4 plates). The manufacture of hollow forged seamless drums for boilers intended to work at steam pressures of 800 lb. per sq. in. is described and illustrated. For the largest drum, measuring 44 ft. 5 in. in length and having an outer diameter of 5 ft. 3 in. with a wall thickness of $4\frac{1}{2}$ in., the ingot of acid open-hearth steel weighed 165 tons; it was cast from four open-hearth furnaces, and the composition of the metal in each was carefully adjusted so as to counteract the tendency of carbon to segregate to the top. During teeming the mould was rotated at a speed of 4 r.p.m., so that the metal in the mould should be stirred up by the steel flowing in. Analyses were taken at 5 points at the top and 5 at the bottom after cropping and trepanning a 24-in. hole down the centre; they were very uniform and averaged carbon 0.234, manganese 0.556, phosphorus 0.030, sulphur 0.024, silicon 0.238 per cent. The mechanical strength properties required were a proof load of 11 tons per sq. in., tensile strength 26 to 31 tons per sq. in., yield point not less than 13 tons per sq. in., elongation 25 per cent. on 3-in. gauge length, and 45 per cent. reduction of area. Strips of 9 in. \times 1 in. \times $\frac{3}{4}$ in. must withstand cold-bending round a $\frac{3}{4}$ -in. mandrel until the ends met.

Weldless Forged Vessels for High-Pressure Work. (Kruppsche Monatshefte, 1929, Vol. 10, Jan.-Feb., pp. 1-10). The manufacture of weldless forged vessels for use where very high pressures are required, suitable materials, dimensions, &c., are discussed.

Preparing Steel Stock for Lock Washers. G. Keenan. (Heat Treating and Forging, 1928, Vol. 14, Nov., pp. 1278-1281). The 1929—i.

production of the cold-finished stock required for automatic methods of manufacture is described.

Cold-Drawn Shapes for Turbine Blades. (Heat Treating and Forging, 1928, Vol. 14, Dec., pp. 1405-1406). The preparation of carbon and alloy steel shapes for the blades of steam rotors is described. Accuracy and smooth finish are attained by cold-drawing.

Performance of Special Steel Sheets. (Heat Treating and Forging, 1929, Vol. 15, Mar., pp. 328-329). The drawing of radiator shells is briefly outlined, and the economic and technical advantages gained by the use of special drawing sheets are discussed. The composition and other details of the sheets are not, however, given.

Note on Stamping. M. Lebon. (Arts et Métiers, 1928, Vol. 81, Nov., pp. 417-422). The manufacture of parts of various shapes, such as rings, spring shackles, motor-car axles, &c., by stamping is described, with illustrations.

The Study, by Means of X-Rays, of the Phenomena Accompanying Stamping. J. J. Trillat. (Chimie et Industrie, 1928, Vol. 20, Oct., pp. 618-622). The author describes the apparatus used and the results obtained in the study of the effect of stamping on the internal structure of the sheet steel. The stamping causes the crystals of the metal to align themselves in such a way that the diagonal of the cube face becomes an axis of rotation and takes up a position parallel to the neutral fibre in the deformed part. The orientation is specially marked in those parts where the curvature is severe or where curvature in two directions exists. The orientation effect is accompanied by a considerable reduction in the grain-size. Stamping gives rise to internal stresses which are the more intense as the curvature is more severe; they are distributed symmetrically about the axis of orientation.

The Stamping Test. Rudeloff. (Die Giesserei, 1929, Vol. 16, Mar. 8, pp. 218-219). The relative sizes of the stamp and die are discussed.

ROLLING-MILL PRACTICE.

Theory of Rolling in the Light of Recent Experimental Researches. I. Pavloff. (Journal of the Russian Metallurgical Society, 1929, No. 1., pp. 39-82). (In Russian.)

The Principles of Rolling. V. P. Kryshanovsky. (Journal of the Russian Metallurgical Society, 1928, No. 3, pp. 1-40). (In Russian.)

Rolling-Mill Practice. F. L. Estep. (Iron and Steel Engineer, 1929, Vol. 6, Mar., pp. 122-127). The author has recently visited Germany, Spain, and Russia, and records his observations on rolling-mill practice in those countries.

Experiments on the Rolling and Forging Processes. G. Sachs. (Mitteilungen der deutschen Materialprüfungsanstalten, 1929, Sonderheft V., pp. 130-137). See Journ. I. and S.I., 1927, No. II. p. 563.

Power Requirement Studies Carried out on Free Running Electrically Driven Rolling-Mills. A. Werth. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 301-308). The ascertainment of the power required to roll any particular section is an important factor in estimating costs of production. The total kw.-hr. expended per ton of material rolled per hr. are of course much higher in the case of rolling heavy sections than when rolling light sections or thin sheets. In order to obtain comparative figures of the power expended per ton of material rolled independently of the hourly production it is necessary to measure the work expended over and above that necessary to drive the mill when running idle. This factor is termed the "excess-work load." The value of it in kw.-hr. per ton is obtained by recording the work done when the mill is running idle for a certain time and when running for the same time on a particular section. The amount of the excess-load work is shown to be affected not only by the size and shape of the section, but also by the design and mode of working the mill. Thus :

Finished Section. Mm.	Initial Section. Mm.	Elongation. Times.	Tonnage. Per hr.	Total Work. Kw.-hr. per ton.	Excess- Work Load. Kw.-hr. per ton.
Strips :					
150 × 11.5 .	...	...	25.0	35.8	22.2
150 × 22.3 .	...	...	29.4	24.9	14.7
Sheets :					
4.9 thick .	...	...	12.9	44.0	34.7
2.9 thick .	...	...	5.6	90.5	58.8
Rods :					
13 diam .	80 sq.	48.5	...	81.0	38.0
10 diam. .	80 sq.	82.5	...	85.5	41.0
Wire :					
12 diam. .	120 sq.	128.0	...	59.3	32.5
10.5 diam. .	120 sq.	166.0	...	65.6	42.8

The argument is that by attention to design and to lubrication and cleanliness, the power required to run the mill idle should be kept as

low as possible. Some interesting diagrams are plotted showing the excess-work load and corresponding elongation for a large number of sections. The author admits that all the calculations can be upset by variations of temperature of the rolled material.

Power Requirements and Efficiency of Sheet and Armour Plate Rolling-Mills. F. Hammerschmidt and H. Babin. (*Archiv für das Eisenhüttenwesen*, 1928, Vol. 2, Dec., pp. 367-370). The most comprehensive series of trials made to ascertain the power requirements of rolling-mills was that by J. Puppe at Witkowitz in 1912. (*See Iron and Steel Institute, Carnegie Scholarship Memoirs*, 1910, Vol. 2, p. 271.) An analysis of the power given out by the motor during a single pass showed that it was expended in: (1) Losses in motor and mill running idle; (2) excess of the losses under load—(a) in the motor, (b) in the pinions, (c) in the roll bearings; (3) the acceleration losses, due to increase in the energy of the moving masses during the pass; (4) the work required for deformation; (5) the losses due to slip between the rolls and the piece and due to shocks. Notwithstanding that several sources of error have since been noted, certain definite laws governing the power consumption are recognisable. Some results of further tests by Puppe on a plate mill at Witkowitz and on a Swedish and an English mill are recorded, and all these indicate the dependence of the degree of efficiency of the mill and motor on the temperature of the piece and the pressure on the rolls. In the armour plate mill the efficiency ranged from 25 to 80 per cent., and in the plate mill from 15 to 87 per cent. An analysis of the power consumption is shown diagrammatically for the Witkowitz armour plate mill, and in tables for the English and Swedish mills.

Some Matters of Importance in the Rolling of Steel Sections. S. Stansfield. (Paper read before the Cleveland Institution of Engineers, Jan. 14, 1929: *Iron and Coal Trades Review*, 1929, Vol. 118, Feb. 1, pp. 169-170). The aim of the paper is to find simple rules for guidance in equalising the power required in a succession of reductions of area of section in rolling. The experimental basis of the work is Dr. Puppe's text-book, "Experimental Investigations on the Power Required to Drive Rolling-Mills," published in 1910.

Roll Pressure and Rolling Work in the Cold-Rolling of Metals. E. Siebel and A. Pomp. (*Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1929, Vol. 11, pp. 73-85). Cold-rolling tests on bands of mild and hard steel and of copper showed that only 10 to 40 per cent. of the energy supplied by the mill motor was employed in changing the shape of the material. The deformation efficiency of the cold-rolling process—that is, the ratio of the work theoretically required for the deformation process only to that put into the rolling-mill—decreases with a decrease in the ratio of the thickness of the rolled material to the roll diameter, with increasing reduction

of draught, and with increasing friction between the rolls and the material. The simplest means of improving the efficiency is to lubricate the material or reduce the roll diameter; the employment of both means together is limited by the fact that with decreasing roll diameter and decreasing friction between the rolls and the material, the permissible reduction of draught with which the rolls can still grip the material and draw it through is also decreased. The power lost in the mill is accounted for principally by friction in the roll bearings; its proportion to the total power consumed is so great that attention should be given to any proposal for reducing it. In the ordinary 2-high mill the form of the bearings is limited by the diameter of the rolls, but in 4- and 6-high mills the working and the backing-up rolls may be so proportioned that efficient working, low roll pressure, and suitable roll bearings are made possible.

Spring in Rolling-Mills : its Importance from the Technical Point of View. On a New Housing Practically Free from Spring. J. Roux. (*Revue de Métallurgie, Mémoires*, 1928, Vol. 25, Dec., pp. 649-662). The author commences by discussing the modern tendency towards the requirement of very close tolerances in rolled products, and points out that this can only be satisfied by the provision of rolls which are capable of very fine adjustment. He then reports the results of measurements made on products rolled in mills of the ordinary type to indicate what degree of variation of dimensions may be expected in general practice. The author next describes a new type of housing which is intended to enable the operator to adjust his rolls very accurately. The top bearing of the upper roll is provided with two inclined planes set at a very obtuse angle; pressing downwards on these are two wedge-shaped pieces. A horizontal right- and left-hand screw engages with the blocks in such a way that the turning of the control handle in one direction draws the two wedges together, and, as the wedges cannot rise, the roll bearing is pressed down; turning the control handle in the opposite direction separates the wedges, so allowing the roll bearing to rise. The author quotes results to show that with billets measuring 200×15 mm., rolled in two lengths of 50 m. (the bars were cut in two before the last but one pass), on 45 tons, 70 per cent. of the bars had a tolerance of 0.1 mm., and all of them satisfied a tolerance of 0.25 mm., and this despite the fact that the rolling was carried out in one heat at irregular temperatures. In the succeeding sections of his article, the author discusses the spring in mill housings and the influence of spring on tolerances from the theoretical point of view, and also deals with the estimation of rolling stresses and their variation as a function of temperature. In the final section he touches upon the use of wooden bushings for precision rolling.

Roll Pass Design. W. Trinks. (*Rolling-Mill Journal*, 1929, Vol. 3, Jan., pp. 13-18; Feb., pp. 67-70; Mar., pp. 115-118; Apr., pp. 179-183). The first article consists of a general introduction to the subject

of roll pass design, a definition of terms is included, and a brief description is given of various types of rolling-mills. Problems of design are also discussed. In the February issue the author describes the forces and bending moments acting upon the rolls, as well as the factors which determine the roll stress. In the March issue an example is given of how the forces acting on the rolls are calculated, based upon bending moments, arc of contact, and compression resistance. The general factors which modify stresses in rolls and which must be considered in their design are described in the April issue.

Utilisation of the Dead Pass in Three-High Rolling-Mills. H. Crämer. (Stahl und Eisen, 1929, Vol. 49, Apr. 18, pp. 531-535). Designs of roll drafting in a three-high rail finishing-mill are given, showing how every pass between the three rolls may be utilised. The design is based on the four-roll system, at the same time obviating the disadvantages of that system.

The Stress on Hot Sheet Mills. L. Weiss. (Zeitschrift für Metallkunde, 1928, Vol. 20, Nov., pp. 389-393). The causes of roll breakages and their avoidance are discussed. A method of calculating the draft which will correspond to a given stress in the roll is explained, and curves showing such values for iron, copper, and aluminium are given. Examples are worked out, and the results compared with drafts actually applied. From this it appears that the stresses in the rolls often exceed that value for which the construction of the mill is suited.

The Influence of the Rolling Temperature on the Elongation, Spread, and Work of Rolling of Various Carbon Steels in a Wire-Rod Mill. K. Hopper. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 283-299). Experiments carried out on the roughing and finishing stands showed that carbon steels behaved differently according to whether the bars were taken direct from one train to the other or were reheated. When rolling after heating, the rolling temperature had comparatively little effect on the elongation and spread; with decreasing rolling temperature the elongation decreased, the spread increased, and the strength of the rod increased almost linearly. Carbon content and method of production affected the rolling in that basic Bessemer steel always gave a better elongation and smaller spread, while a 0.45 per cent. carbon open-hearth hard steel gave a smaller elongation and greater spread; other open-hearth steels with 0.05, 0.22, and 0.72 per cent. of carbon gave intermediate values. When rolling without reheating, decrease of rolling temperature caused a marked decrease of elongation and increase of spread, down to 1000° C.; below 950° C., the elongation increased again and the spread decreased. Here, also, the strength of the rod rose linearly with the falling rolling tempera-

ture, and the carbon content and method of production had the same, but more marked, effect as when rolling after reheating. In explanation of the different behaviours of the materials are suggested the different frictional relations between the pass and the surface of the rod, and the decisive effect of the temperature distribution in the cross-section of the rod on the elongation and spread. The work done in rolling the various materials was measured; the highest value was recorded with the 0.45 per cent. carbon open-hearth hard steel.

The Efficiencies of the Drawing and Cold-Rolling Processes Compared. E. Siebel. (Stahl und Eisen, 1929, Vol. 49, Apr. 25, pp. 561–566). The author presents calculations for the purpose of comparing the efficiencies of the two principal processes by which the deformation of steel in the cold state is performed—namely, the wire-drawing process and cold-rolling as carried out in a rolling-mill. On a draw-bench, and with a well-lubricated die, the greater the reduction in any draft the higher is the efficiency. In drawing a wire rod with carbon 0.03 per cent., with an initial tensile strength of 39 kg. per sq. mm., the efficiency rose from 35 per cent. with a 10 per cent. reduction of area to about 72 with a 52 per cent. reduction. The optimum angle in the die was found to be 6° . With another wire rod with carbon 0.6 per cent., and initial tensile strength of 96 kg. per sq. mm., the efficiencies were, respectively, about 42 and 80 per cent. for reductions of 9 and 52.6 per cent. The same two classes of material were then cold-rolled in a rolling-mill of ordinary construction, and after deducting the power required to run the mill idle (about 2.0 kw.), the efficiency in rolling the 0.03 carbon steel was from 10 to 40 per cent., and for the 0.6 carbon steel only 10 to 30 per cent. The losses are chiefly the frictional losses in the bearings, and it is considered that if a special light rolling-mill with roller bearings were constructed and with good lubrication of the material the efficiency in cold-rolling would be greatly improved. In an ordinary mill the power consumption in cold-rolling increases in proportion to the square of the rolling speed, but by using rolls of small diameter with roller bearings and lubrication this proportion is very much reduced.

Special Steel Rolls for Rolling-Mill. N. Guédras. (Aciers Spéciaux, 1929, Vol. 4, Mar., pp. 124–125). The author discusses the composition of rolling-mill rolls. He claims to have obtained good results with material of the following composition: carbon 0.5, silicon 0.2, manganese 0.3, nickel 1.0, and chromium 2.5 to 3 per cent. He also discusses matters affecting the manufacture of the rolls.

Alloy Chilled Rolls for Difficult Machining Problem. P. J. Longnecker. (Iron Trade Review, 1929, Vol. 84, Feb. 28, p. 586). The turning of chilled rolls is briefly discussed, and average cutting speeds for different types of rolls are tabulated. It is stated that a special

steel known as "Circle C" has been introduced for dealing with rolls containing chromium and molybdenum. The average hardness of these rolls is from 70 to 75 scleroscope.

Chilled Plate Rolls and the Causes of their Breakage as Shown by Metallographic Study. N. V. Kolokoloff. (Journal of the Russian Metallurgical Society, 1928, No. 1, pp. 58-76). (In Russian.)

The Use of Roller Bearings in Rolling-Mills. G. Palmgren. (Jernkontorets Annaler, 1928, Vol. 112, p. 116; Stahl und Eisen, 1929, Vol. 49, Jan. 24, pp. 101-108). A number of special types of roller bearings for rolling-mills are illustrated and described, including a device for the prevention of pressure in the direction of the axis of the roll. The radial pressure is taken by double-roller bearings, one of which is supported on the knife-edges of two rockers which rest on a flat bearing surface so as to allow for play in the direction of the axis. The application of roller bearings to universal plate-mills and to mills for cold-rolling strip and hoops is discussed.

Development in Application of Anti-Friction Bearings to Roll Necks. E. C. Gainsborg. (Rolling-Mill Journal, 1929, Vol. 3, Jan., pp. 19-22). A general discussion of fundamental principles and limitations involved in the application of anti-friction bearings to roll necks.

Anti-Friction Bearings for Roll Necks. E. C. Gainsborg. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 270-271).

Selection of Anti-Friction Bearings for Roll Necks. J. H. van Campen. (Rolling-Mill Journal, 1929, Vol. 3, Jan., pp. 31-34). Conditions governing successful application of roller bearings to roll necks are discussed, and types of anti-friction bearings and typical installations are illustrated.

Rolling-Mill Lubrication. L. P. Tyler. (Paper read before the American Society of Mechanical Engineers: Rolling-Mill Journal, 1929, Vol. 3, Feb., pp. 71-74; Blast-Furnace and Steel Plant, 1929, Vol. 17, Apr., pp. 565-568). A discussion of a number of factors involved in the lubrication of rolling-mill driving equipment.

Friction Conditions, Power Consumption, and Lubrication Practice in Ironworks. F. Heyd. (Stahl und Eisen, 1928, Vol. 48, Nov. 22, pp. 1637-1642). A series of experiments extending over some years was made to determine the best kinds of bearing metal and of lubricating oils for use in rolling-mills, and working diagrams are given showing the effect of different lubricants on the power consumption of

a rolling-mill. Vegetable oils, particularly rape-seed oil, give the best results, or a mixture of rape-seed oil with ordinary machine oil is about equally good in reducing friction. Tin or tin alloys are the most suitable materials for withstanding the wear due to heavy loads on the bearings, which may vary in working from 750 to 9000 lb. per sq. in.

Copper as Core Material in the Manufacture of Drill Steel. R. A. Bedford. (Engineering and Mining Journal, 1928, Vol. 126, Oct. 20, pp. 625-626). Three methods of producing hollow drill steel are briefly described. The billet may be drilled, the hole filled with sand, the billet rolled down and the sand removed, or the billet may be pierced and rolled over mandrels, the last few passes being made without support, as such small mandrels are not convenient. These two methods are said to produce drill steel which suffers too many failures. The process adopted by the author's firm consists in drilling out the billet and filling it with copper; the billet is rolled down and the copper is removed. Details of procedure are not given. The structure of the "copper-cored" steel is dense and the surface of the hole is not decarburised.

The Manufacture of Broad-Flanged Parallel Girders. F. Trappiel. (Stahl und Eisen, 1928, Vol. 48, Nov. 1, pp. 1533-1545). For the rolling of wide-flanged beams with parallel flanges the grooving of the rolls is so designed as to produce even stretching of the material in all parts of the section during rolling, so that the finished girder shall be entirely free from internal stresses. The form of rolls and method of rolling are the subject of a patent D.R.P. No. 355588.

The Manufacture of Broad Flange Parallel Beams. F. Trappiel. (Rolling-Mill Journal, 1929, Vol. 3, Mar., pp. 131-134). An abridged translation of the above article.

Mill for Producing Trussed Joists. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Apr., pp. 555-556). **Rolling-Mill Equipped with Unique Drive.** (Rolling-Mill Journal, 1929, Vol. 3, Apr., pp. 163-166). An illustrated account is given of a continuous mill used for slitting and expanding small I-beams to produce light trussed joists for building construction. It consists of three stands, with accessories, including an approach table, pinch rolls, delivery rolls and a run-out table. One feature is the method of drive, no pinion stands being included in the installation. The three work stands are driven directly through a combination of bevel and back gears, and the accessory equipment by chain and gear drives from the work rolls. All roll necks and gear shafts are equipped with Timken bearings. The first or entry stand pinches the beam and delivers it to the slitting rolls; the second stand operates the slitting rolls which form the strands in the finished beam; and the third stand operates the finishing rolls and delivers the joist to the hot bed. Since the distance between the last stand and the middle, or

slitting, stand varies with the size of joist to be rolled, provision has been made for moving both the last stand and its bevel gear drive on rails. In all but the straightening and finishing stands the work rolls are overhung, being keyed to an extension of the roll shaft which projects beyond the housing. This construction is said to facilitate the removal of the rolls. The mill is in operation at the Buffalo plant of the Kalman Steel Co., Chicago.

Special Design Marks New Barton Rail Steel Mill at Chicago. F. B. Pletcher. (Iron Trade Review, 1928, Vol. 83, Nov. 15, pp. 1242-1243, 1276). The layout of the new mill of the Barton Steel Company, Chicago, for the production of bars and other sections from old rails is described. The main mill equipment consists of a six-stand 3-high mill driven directly from a mill motor, which operates only the rolls. The drive is without speed reducers or similar mechanism.

Automatic Seamless Pipe Mill. S. G. Koon. (Iron Age, 1928, Vol. 122, Nov. 29, pp. 1353-1358). Two automatic seamless pipe mills at the Aliquippa plant of the Jones and Laughlin Steel Corporation, Pittsburgh, are described and illustrated. The first mill is capable of producing pipe from $6\frac{5}{8}$ to $14\frac{3}{8}$ in. outside diam., and the second mill from $2\frac{3}{8}$ to $6\frac{5}{8}$ in. outside diam. The blooms are heavy, ranging from 8×8 to 14×14 in. in section and about 10 ft. in length. These are pickled and passed through continuous furnaces before being rolled in two stands of 2-high rolls for the production of rounds forming the blanks for the tube mill. The rounds are then passed through the tube mill furnaces and enter the piercing machine. This consists of a Mannesmann type of cross roll with mandrel. On leaving the piercing machine practically all the blanks are passed through the expander or second piercer and from thence to the plug mill. In both these mills the action is to reduce the wall thickness of the tubes and increase the diameter. They are next passed through the reeling machines, the operation of which is similar to that of the piercing mills. The type and setting of the rolls are similar but of smaller angle, while the plug over which the pipe passes is slightly larger than the inside diameter of the finished pipe. The tubes are next passed through the sizing rolls, which reduce them from the slight over-size at which they left the reelers to the exact diameter required for the finished pipe.

Modern Cold-Rolling Plants. (Demag News, 1929, Vol. 3, Jan., pp. 1-12). Recent types of cold-rolling mills and auxiliary equipment, including pickling machines, buckling or desintering mills, and winding, straightening, cutting, and shearing machines, are described and illustrated.

Adds Cold-Rolled Strip Department. (Iron Age, 1928, Vol. 122, Dec. 27, pp. 1629-1631; Iron Trade Review, 1928, Vol. 83, Dec. 20,

pp. 1560-1562). Particulars are given of the new cold-rolled strip plant of the Sharon Steel Hoop Co., Sharon, Pa. The rolling equipment consists of three sets of tandem roughing rolls, with reels and coilers and complete handling equipment for materials and rolls. There are seven sets of finishing mills with auxiliary equipment, similar to the roughing mills. Other finishing equipment consists of slitters, roller levellers, edging mills, rewinders, polishing machines, oiling machines, and shears.

Design and Operation of Strip Mills. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Nov., pp. 1454-1459). The article is an English translation of Reports 60 and 61 of the Rolling-Mill Committee of the Verein deutscher Eisenhüttenleute, the authors of which were C. Schulz and H. von Avanzini. The former report described the strip mills of the firm of Theodor Wuppermann at Schlebusch-Manfort, and the latter the strip mill of the Bochumer Stahlindustrie. The original texts appeared in *Stahl und Eisen* (see Journ. I. and S.I., 1928, No. II. p. 348).

Semi-Continuous Rolling-Mill for Steel Strip. (Demag News, 1929, Vol. 3, Apr., pp. 29-33). A complete illustrated account is given of the semi-continuous strip mill and its auxiliary equipment at the August-Thyssen-Hütte, Dinslaken. Strip is rolled in widths of 3.95 to 17.7 in., and in thicknesses from 0.049 to 0.118 in. While rolling is in progress the train itself only needs a crew of four men and a foreman to superintend it. The total time taken to roll down a bloom measuring $11 \times 3 \times 40$ in. into strip of 11×0.108 in. is not more than $48\frac{1}{2}$ sec.

On the Production of Tube Strip. E. Stahl. (Röhrenindustrie, 1929, Vol. 22, Feb. 14, pp. 54-56). The author discusses the raw materials and the mills used for the production of steel strip for the manufacture of tubes.

Rolling Bar Plates and Hot Strips. J. B. Ink. (Paper read before the American Institute of Electrical Engineers: Iron Age, 1929, Vol. 123, Apr. 18, pp. 1070-1071). The general arrangement of the bar plate and hot strip mill recently placed in service by the American Rolling-Mill Co., Middletown, Ohio, is described. The mill consists of eleven stands. The first seven constitute the bar mill and normally reduce the sheet to about $\frac{3}{8}$ -in. thickness. The last four stands are the hot strip mill. Between stands 7 and 8 are a run-out table, a transfer and a bar piler for taking off sheet bar or other heavy-gauge product. Stands Nos. 1 to 4 are independent as regards speed, while Nos. 5 to 7 and Nos. 8 to 11 are interdependent. The first four stands are each driven by a wound-secondary induction motor, and are equipped with flywheels. Stands Nos. 5 to 11 are driven by 600-v. d.c. adjustable speed motors.

Sheet Steel for Automobile Bodies. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Nov., pp. 1449-1453). The continuation of a series of articles (*see* Journ. I. and S.I., 1928, No. II. p. 346). The present instalment reviews the various methods employed in testing sheet steel for such properties as ductility, hardness, tensile properties, &c., and these characteristics are compared with the results of microscopical examination.

Rolling High-Grade Auto Sheets. W. H. Melaney. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 91-93). Some of the problems involved in rolling sheets for the automobile industry are discussed. The double mill loose pack system of rolling produces sheets with surfaces much superior to other systems of rolling. An illustration is given of a method of applying steam to the rolls.

Four- and Six-Roll Stands in American Rolling-Mills. E. Link. (Stahl und Eisen, 1929, Vol. 49, Jan. 10, pp. 37-40). The article describes the types of sheet rolling-mills with backing rolls and fitted with roller bearings. The continuous sheet rolling-mills of the Weirton Steel Co. are described.

Reversing Sheet Mill Designed to Eliminate Heat Losses. L. Cammen. (Iron Trade Review, 1929, Vol. 84, Apr. 11, pp. 994-995). Particulars are given of a 2-high reversing sheet mill under construction in America. The mill is equipped with high-frequency coils between the housings to heat the sheets during the rolling process.

Steel Sheet Rolling in the United States. (Iron and Coal Trades Review, 1928, Vol. 117, Dec. 21, p. 910). A digest is given of the discussion that took place before the American Society of Mechanical Engineers on various problems connected with the rolling of steel sheets.

Sheet and Tube Tin Mill at East Chicago. F. W. Manker. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 291-292, 304). An account is given of the plant of the Youngstown Sheet and Tube Co., for the manufacture of tin sheets.

Schedules First Tin-Mill Plant West of Mississippi River. A. J. Hulse and C. E. Dougan. (Iron Trade Review, 1929, Vol. 138, Mar. 21, pp. 782-784; Blast-Furnace and Steel Plant, 1929, Vol. 17, Apr., pp. 557-559). Particulars are given of the equipment of the new tin-mill plant of the Columbia Steel Corporation, Pittsburgh, California. The hot mills consist of eight 28 × 34 in. roll stands driven by a 180 H.P. motor through a single herring-bone reduction set. The mills are arranged to operate on the single mill, three-part system. Each mill is served by a continuous pair furnace and a sheet furnace, both oil-fired by low-pressure burners.

Rolling-Mill Statistics, 1928. (Iron and Steel Engineer, 1929, Vol. 6, Feb., pp. 93-94). A table is given showing the new rolling-mill equipment put in operation in the United States during 1928. The type and style of mill, motor characteristics, and method of drive are given.

Electricity's Contribution to the Iron and Steel Industry. (Iron and Steel Engineer, 1929, Vol. 6, Jan., pp. 25-65). A complete list is given of the main roll drives installed in the American iron and steel industry at the end of 1928. The tabulation shows the h.p., r.p.m., voltage, cycles, type, and size of mill, method of drive, date of purchase, name of plant and location. A classified list also gives the types of installation in blooming mills, plate mills, rail and structural mills, bar and billet mills, sheet bar and skelp mills, sheet and tinplate mills, rod mills, piercing mills, tube mills, strip and hoop mills, merchant mills, wire mills, wheel mills, and non-ferrous mills. The multi-speed drives, a.c. speed sets, d.c. adjustable speed drives, and reversing blooming-mill drives are also tabulated.

Development in Electricity and Power. G. Fox. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 78-80). Progress in the application of electricity to rolling-mill plant, blast-furnace charging gear, and gas-cleaning plant is reviewed.

Developments in Mill Drives in 1928. J. D. Wright. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 86-87, 98). The new 36-in. reversing universal slabbing mill at the Steubenville (Ohio) works of the Wheeling Steel Corp'n. is briefly described; the horizontal and vertical rolls will be independently driven by two separate motors, and the control gear will maintain the correct speed ratio between the two drives without the use of any mechanical gearing. Notes concerning a number of other new mills and drives are given, and other electrical developments in mills and their auxiliary plants are touched on.

Large Expansion in Electric Drive. S. G. Koon. (Iron Age, 1929, Vol. 123, Mar. 14, pp. 743-744). Additions made to the electric-drive equipment of rolling-mills in America in 1928 are tabulated, and the growth in application of electric drive to main rolls since 1905 is shown. Other tables show respectively the number and size of large motors operating various types of mills, and the range of sizes of mill motors.

Electrical Applications in Steel Plants. A. F. Kenyon. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 99-102, 106). Brief mention is made of motor drives installed during the year 1928 that possess features of interest. A table, containing the names of 78 plants, shows the type of mill and drive installed, and details of the electric motors supplied for them during the year.

Electrical Developments in the Iron and Steel Industry. D. W. Dean. (Rolling-Mill Journal, 1929, Vol. 3, Jan., pp. 23-26, 34). The author reviews recent applications of adjustable and constant speed drives to rolling-mills.

Starting Characteristics of Steel Mill Synchronous Motors. H. H. Angel. (Iron and Steel Engineer, 1929, Vol. 6, Apr., pp. 147-156). For a number of years the wound rotor induction motor has been used on practically all steel mill constant speed main roll drives. This motor is admirably suited for such service, due to its ability to produce high starting torques and carry sustained overloads, which are requirements in steel mill service. However, inherent in the best motors of this type is its low-power factor, which penalises the generating and distribution system with wattless current. Synchronous motors have been used on air-compressors, motor-generator sets, and in other applications where the starting duty does not require more than 20 to 30 per cent. of full-load starting torque. In low-speed applications the first cost is somewhat less than its wound rotor induction motor competitor, and its efficiency is slightly higher. In the last three years improvements in automatic starting equipment and in the designs of synchronous motors, whereby greater starting torque with a minimum current input is available, have led to an increased number of installations.

Adjustable Speed Main Roll Drives. M. H. Morgan. (Iron and Steel Engineer, 1928, Vol. 5, Oct., pp. 429-448; Nov., pp. 467-489). This paper contains a great deal of information bearing upon the application and use of adjustable speed a.c. and d.c. main roll drives. The October issue deals with d.c. drives, and with the various methods of obtaining more than one speed from the standard induction motor without the use of auxiliary machines. The general principles of the Kramer, Scherbius, and frequency-converter sets are outlined. The November issue contains a detailed description of these sets, together with the brush-shifting a.c. motor. A comparison is also made of a.c. and d.c. drives.

Recent Developments at Sparrows Point. F. O. Schnure. (Iron and Steel Engineer, 1929, Vol. 6, Jan., pp. 19-24). An illustrated account is given of additions made to the rolling-mill equipment at the Sparrows Point plant of the Bethlehem Steel Co., with special reference to the electric driving installations.

Specifications of 40-in. Reversing Blooming-Mill Drive. (Iron and Steel Engineer, 1928, Vol. 5, Oct., pp. 448-451). This specification covers electrical apparatus to drive a 2-high reversing mill. The equipment consists of a reversing d.c. roll-drive motor receiving its power from a suitable motor-generator flywheel set, and complete

control equipment. The specification is submitted as a guide in preparing specifications of this nature.

The Rod-Mill Electrification at the South Works of the American Steel and Wire Co., Worcester, Mass. R. H. Bryant. (Iron and Steel Engineer, 1928, Vol. 5, Dec., pp. 501-507). The scheme for the electrification of the rod mills at this plant is described in detail.

Rod-Mill Electrification in the South. G. Fox. (Freyn Design, 1929, Feb., pp. 8-9). **Gulf States Steel Company Electrification.** R. H. Wright. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Jan., pp. 162-163). The electric driving equipment of the rod mills of the Gulf States Steel Co. is described. Five synchronous motors are used in a system of subdivided or group drives.

Electrification of Rail Steel Re-Rolling Mill. A. J. Whitcomb. (Freyn Design, 1929, Feb., pp. 17-20; Blast-Furnace and Steel Plant, 1929, Vol. 17, Mar., pp. 415-417, 435). The electric driving equipment of the rail re-rolling mill at the Pollak Steel Co., Marion, Ohio, is described and illustrated.

Transmission Ropes in Rolling Mills. N. A. Sobolevsky. (Journal of the Russian Metallurgical Society, 1928, No. 3, pp. 41-54). (In Russian.)

ROLLING-MILL MACHINERY.

Electric Induction Roll Heaters. (Iron and Coal Trades Review, 1928, Vol. 17, Dec. 7, pp. 832-833). An electrical device for warming up sheet and tinplate rolls is described and illustrated. The heater consists of a strip of copper wound on edge with the under-sides connected by flexible leads, the whole being braced together and supported by two rods placed over the rolls. The rolls themselves are covered with a sheet of asbestos cloth, which prevents loss of heat by radiation and at the same time protects the roll heater from the heat of the rolls. The heater can be put on or taken off within ten minutes, all the connections of the coils being made by tightening one bolt, and none of the permanent mill fixings need be removed. The arrangement of the transformer depends on the number of roll heaters in use in one line of mills. Each heater takes approximately 50 to 60 kw. to raise the temperature of a pair of rolls 42 × 30 in. diam. to 300° C. in 12 hr., consuming from 600 to 720 units. The type of heater described is in use at the Shotton Works of John Summers & Sons, Ltd.

Rolling-Mill Couplings. A. Haag. (Stahl und Eisen, 1928, Vol. 48, Nov. 8, pp. 1581-1584). Various types of flexible couplings for rolling-

mills are well illustrated and described, among them the Francke coupling, the Thomas or Thomson coupling, and the David coupling of the Allis-Chalmers Manufacturing Company. The principle is much the same in all these types, the coupling consisting generally of two thick flanges, each provided with a number of sockets, those in the face of one flange corresponding exactly to those in the other. Tongues of tough spring steel are fitted loosely in the sockets of one flange and project into the corresponding sockets in the opposite one. Special reference is made to the Bibby coupling, which is of large diameter. On the periphery of the two flanges are cast strong steel projections, somewhat like the teeth of a spur wheel. A strong serpentine spring of flat steel is laid round the flanges, fitting in the grooves or spaces between the projections. By this means a great degree of flexibility is secured, and the coupling has been successfully used where rigid couplings have failed in a very short time. A modification of it, so as to form a sliding clutch coupling, has been introduced.

Chain Transfer Table for Blooms. (Blast-Furnace and Steel Plant, 1928, Vol. 16, Dec., pp. 1559, 1570). **Blooms Routed in Four Directions.** (Iron Age, 1928, Vol. 122, Nov. 8, pp. 1166-1167). Particulars are given of the chain transfer table in operation at the new plant of the Timken Steel and Tube Co., Canton, Ohio. Material coming from one operation may be diverted to any of four others. The table has an overall length of 81 ft., and a width sufficient to accommodate either two rows of 9-ft. blooms, or a single row of 18-ft. blooms. Bloom travel is accomplished by four endless chains, provided with carrying dogs, which extend 4 in. above the surface of the skid rails. The chains are driven from four sprockets mounted on a common shaft at the delivery end of the table, and run over four spring sheave take-up sprockets at the shear table end. The drive consists of a 90 H.P., 220 v. compound wound, mill-type motor, which drives the sprocket shaft through a reduction unit, giving a chain speed of 150 ft. per min.

Individual Motor Drives for Roll-Out Tables. J. C. Dobelblower. (Rolling-Mill Journal, 1929, Vol. 3, Jan., pp. 35-36, 40). The application of individual electric motors to the rolls of roll-out tables is dealt with, and types of motors and their constructional features are described.

Thin Sheet Doubler. (Kruppsche Monatshefte, 1929, Vol. 10, Mar., pp. 35-37). The Krupp-Gruson electrically operated sheet doubler is illustrated and described. (See Journ. I. and S.I., 1928, No. II. p. 353.)

MANUFACTURE OF WIRE.

The Power Required and the Work Done in the Cold-Drawing of Wires. A. Pomp, E. Siebel, and E. Houdremont. (Mitteilungen aus

dem Kaiser-Wilhelm-Institut für Eisenforschung, 1929, Vol. 11, pp. 53-72). The power requirements and the work done in cold-rolling steel and copper wire were measured, and the influence of the material, the reduction of draught, the shape of the die, the drawing speed, and the lubrication were studied. As a standard of reference, the efficiency of the process was used—that is, the ratio of the work theoretically required to carry out the deformation process only to that actually recorded by measurement. Speed of drawing had only a small influence on the power required and on the work done. With increasing reductions of draught, the efficiency increased. An optimum value for the efficiency was obtained when the inclination of the walls of the die lay between 6° and 12° ; as the reduction increased this optimum value moved from the smaller towards the larger angles. Lubrication had the greatest influence on the efficiency; the best results were obtained with a lubricant composed of lime and rape oil. The amount of reduction permissible was dependent on the degree of "strain," which is the quotient of the average longitudinal stress and the tensile strength of the wire running out; the degree of strain increased with increasing reduction and with the total change of shape of the material. The shape of the die and the lubrication affected the ductility in the same way that they did the efficiency.

On the Theory of the [Wire-] Drawing Process. G. Sachs. (Mitteilungen der deutschen Materialprüfungsanstalten, 1929, Sonderheft V., pp. 137-138). A mathematical study of the forces exerted when a wire is drawn through a die.

New Mill Treats Wire Manufacture as a Handling Problem. (Wire and Wire Products, 1929, Vol. 4, May, pp. 152-154, 174; Iron Age, 1929, Vol. 123, May 2, pp. 1206-1211). The layout and equipment of the new wire mill of the Sheffield Steel Corporation, Sheffield, Missouri, are described and illustrated.

FURTHER TREATMENT OF IRON AND STEEL.

PYROMETRY.

Automatic Temperature Regulator. M. Astruc. (*Arts et Métiers*, 1928, Vol. 81, Dec., pp. 463-468). When an alternating current is passed through an electro-magnet with a variable air gap, the intensity of the current is a function of, and within certain limits is proportional to, the size of that air gap. Advantage of this fact is taken in the automatic temperature regulator described in the article. The pyrometer consists of a sheath tube of metal suitable to resist high temperatures, the lower end of which is closed; within this and touching its closed end is the "transmitter" tube, the coefficient of expansion of which differs from that of the sheath. Within the head of the pyrometer, rigidly attached to the sheath tube, is a system of springs and a lever; the relative expansions of the sheath and the transmitter tube cause the lever to move in such a way that the air gap of an alternating current electro-magnet is varied. In electrical connection with the pyrometer is the relay; this is so arranged that when current passes through it a tube containing mercury is tilted so as to complete a circuit, which actuates the electrically operated main switch controlling the furnace. When the temperature of the furnace exceeds the value for which the pyrometer is set, the variable air gap is reduced, the current passing through the relay becomes insufficient to maintain the mercury tube in the tilted position, the current to the main switch is interrupted, and the main switch shuts off the supply current to the furnace. The regulator is stated to maintain the temperature of a furnace within very close limits, and is not affected by external disturbances.

A Pyrometer for Registering Temperatures by Means of Colour Change. G. Naeser. (*Stahl und Eisen*, 1929, Vol. 49, Apr. 4, pp. 464-466). The principle of a new type of pyrometer for measuring temperatures from 900° to 2000° C. is described. The light from the radiating body passes through three filters to the eye of the observer. The first filter absorbs all rays except the red and green. Filters 2 and 3 are geometrically similar wedges: No. 2 absorbs the red rays in an increasing degree, according to the thickness of the part of the wedge through which they pass, while all green rays pass through; No. 3 filter absorbs all green rays in increasing degree and allows the red rays to pass. A mixed red and green colour is thus presented to the eye.

According to the temperature of the radiating body the intensity of the green and red rays passing the filters varies, and it is quite easy to adjust the wedge-shaped filters until the mixed colour is corrected, and according to their position the temperature is read off on a scale to within an accuracy of 13°C .

The Measurement of High Temperatures and the Disappearing Filament Pyrometer. F. A. Foerster. (*Zeitschrift für die gesamte Giessereipraxis*, 1929, Vol. 49, Feb. 19, pp. 29-32). The disappearing filament type of optical pyrometer and its use is described.

HEAT-TREATMENT EQUIPMENT.

The Effect of Furnace Atmospheres on Steel. R. G. Guthrie. (*Transactions of the American Society for Steel Treating*, 1929, Vol. 15, Jan., pp. 96-116). In this paper, which is in the nature of a progress report, the author presents the results of tests with atmospheres commonly met with in various types of heat-treating furnaces. The temperature of 1500°F . was chosen throughout all the tests as being an average temperature for the heat treatment of carbon steels of about the eutectoid composition. The type of steel, conditions of time, pressure, velocity, &c., were constant, the only variable being the different simple gases. The effects of mixing the gases in various proportions are also shown, and the chemistry of the combustion of gas is dealt with in an appendix to the paper. The following practical points are brought out: (1) Scaling or oxidation with oxygen does not cause decarburisation at 1500°F .; (2) carbon dioxide alone is not neutral, and is both a decarburiser and oxidiser of iron and steel; (3) the intelligent use of raw gas, independent of that consumed through the burners, offers possibilities of extremely flexible conditions of furnace atmospheres, and is, therefore, a valuable adjunct to the heat treatment of steel.

Theoretical Considerations in Electric Tunnel Kiln Design. J. Kelleher. (Paper read before the American Electrochemical Society, May 1929). A description is given of a method followed in designing an electric tunnel kiln, from data on the time-temperature cycle required by the materials to be heat-treated.

The Electric Annealing Furnace. E. F. Russ. (*Die Giesserei*, 1929, Vol. 16, Jan. 18, pp. 61-62). The advantages of electrically heated pot annealing furnaces are reviewed; such a furnace and the results obtained with it are described.

Progress Made in the Use of Electric Furnaces for Heat Treatment. A. N. Otis. (*Transactions of the American Society for Steel Treating*,

1929, Vol. 15, May, pp. 767-795). The author shows the present status of electric furnaces, the extent of their use for heat treatment, and describes some new types that have been recently developed. The advantages of electric furnaces for heat treatment are pointed out.

Electric Heating and Heat-Treating. A. N. Otis and W. L. Warner. (Paper read before the Western Metals Congress, 1929 : Heat Treating and Forging, 1929, Vol. 15, Feb., pp. 225-226, 229-230, 233).

Electric Furnaces for Heat Treatments. R. E. Talley. (Paper read before the Industrial Electric Heating Conference, 1928 : Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 93-96).

Electrically Heated Rotary Carburiser. H. M. Chatto. (Iron Age, 1929, Vol. 123, Apr. 25, pp. 1153-1154). An electric rotary carburising furnace is described, which consists of a rotating alloy cylinder inside an electrically heated automatically controlled box-shaped furnace chamber. The heating units comprise three windings of the ribbon type, operating on a 220-v. three-phase circuit, and having a connected load of 70 kw. Parts to be carburised are shovelled into the cylinder together with the carburising compound and are carburised as they are tumbled, resulting in uniform carburisation.

Conveyor Type Electric Furnaces. A. H. Vaughan. (Heat Treating and Forging, 1928, Vol. 14, Nov., pp. 1328, 1331-1332). Various types of mechanism for conveying work through electric furnaces are described.

Continuous Annealing Furnaces for Improving the Quality of Ductile Sheets. H. Fry. (Stahl und Eisen, 1928, Vol. 48, Oct. 4, pp. 1407-1409). This article describes and illustrates some new types of sheet annealing furnaces adopted by some motor manufacturers in the United States. Instead of packing the sheets in boxes, in which the distribution of heat is difficult to control, the centre of the pile not reaching the transformation point for some time after the edges and upper and lower sheets have attained to that temperature, they are placed either singly or in pairs on the rolls of a travelling bed inside a long continuous furnace with a reducing atmosphere, fired with coke-oven gas. The furnace is maintained at a temperature of 1100° C., and the sheets travel through at a speed of 2 to 10 m. per min. The length of the heating chamber is 18 m., and a cooling chamber 12 m. long forms an extension of it. The sheets, after passage through the furnace, are of uniform grain and of high ductility.

Sheets Normalised on a Large Scale. (Iron Age, 1928, Vol. 122, Dec. 20, p. 1577). Particulars are given of the design of a continuous

furnace for the normalising of automobile sheets. It is fired with natural gas and has a capacity of 140 tons per 24 hr. It is 140 ft. long, including loading and unloading tables, and has a heating chamber 100 ft. in length and a cooling chamber 40 ft. long. The width is sufficient to handle 80-in. sheets. The furnace is top and bottom fired, having 60 burners at the top and 60 at the bottom in the heating zone. The sheets are carried through the furnace on roller discs, mounted on hollow, water-cooled shafts that are insulated with highly heat-resisting alloys.

Modern Furnaces for Normalising Sheets. (Heat Treating and Forging, 1928, Vol. 14, Nov., pp. 1321-1324; Blast-Furnace and Steel Plant, 1928, Vol. 16, Dec., pp. 1571-1573, 1578). A description is given of recent equipment for the continuous annealing of sheet steel. The metallurgical features of the process are fully discussed. The furnace described is 155 ft. long and is divided into preheating, soaking, and cooling zones; it is oil-fired, and 20 burners are fitted on each side of the furnace. The furnace is built up of sections each about 5 ft. long and forming the two walls and roof, with joints to allow for thermal expansion. Any of the sections can be removed for repair work, the operation taking less than one hour. The joints between the sections are filled with plastic clay to prevent air from entering.

Double-Deck Conveyor Furnaces Used for Annealing Stampings. (Fuels and Furnaces, 1928, Vol. 6, Dec., pp. 1655-1657). Particulars are given of an installation of five oil-fired furnaces of the double-deck continuous conveyor hearth type, in which the product is heated in the upper chamber and cooled in the lower chamber.

Modernised Equipment for Carburising. F. W. Manker. (Heat Treating and Forging, 1928, Vol. 14, Nov., pp. 1326-1327). The heat treatment plant of the Willys-Overland Co. is described.

Automobile Accessories Heat-Treated. J. B. Nealey. (Heat Treating and Forging, 1928, Vol. 14, Dec., pp. 1450-1452). Heat-treatment plant of the Stewart-Warner Speedometer Corp., Chicago, Ill., is described.

Heat-Treating Ball-Bearing Parts. J. B. Nealey. (Iron Age, 1929, Vol. 123, Apr. 4, pp. 943-945). The equipment and practice at the plant of the Nice Ball Bearing Co., Philadelphia, for the heat treatment of ball-bearing parts are described and illustrated.

Shop of the Timken Detroit Axle Co. H. W. McQuaid. (Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 44-47). The methods and equipment employed by the Timken Detroit Axle Co. for the production of automobile axles are described.

CEMENTATION AND CASE-HARDENING.

Some Cementations of Steel by Special Manganese-Base Alloys. J. Cournot. (Paper read before the Eighth Congress on Industrial Chemistry, Strasbourg, 1928; *abstract*, *Revue de Métallurgie, Mémoires*, 1928, Vol. 25, Dec., pp. 669-670). The paper reports the continuation of the author's work on intermetallic diffusion, and deals with the cementing action of manganese-base ferro-alloys on carbon steels. The ferro-alloys used were: (i) a 15 per cent. spiegel; (ii) a 76 per cent. ferro-manganese; and (iii) an iron-manganese-silicon-aluminium alloy containing Mn 19, Si 21, and Al 10 per cent.

Metallic Cementation. (Metallurgist, 1929, Jan., pp. 7-8). A critical review of Laissus' work on cementation by uranium (*see* Journ. I. and S.I., 1928, No. I., p. 857).

Decarburisation of High-Carbon Steel in "Reducing Atmospheres." J. J. Curran and J. H. G. Williams. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 809-830). The authors have observed many instances of soft skin in high-carbon steel parts which have been hardened under different commercial conditions, but usually when precautions were taken to minimise scaling. Tests were carried out to determine the effect of extremely reducing carbonaceous atmospheres such as those produced by carburising compounds when used to "pack-harden" steel. The tests were carried out on drill rod of the following analysis: Carbon 1.15, manganese 0.28, and silicon 0.19 per cent. Specimens were subjected to annealing treatments, packed in four different mixtures: (1) powdered charcoal; (2) powdered charcoal plus 10 per cent. of sodium chloride; (3) powdered charcoal plus 10 per cent. sodium carbonate; and (4) powdered charcoal plus 10 per cent. barium carbonate. The temperatures and times of heating were as follows: (1) Heated to 1275° F., held at heat 4 hr., cooled slowly with the furnace; (2) heated to 1425° F., held at heat 4 hr., cooled slowly with the furnace; (3) heated to 1675° F., held at heat 2 hr., cooled slowly with the furnace. The tests indicated that carburising packing mixtures may be either carburising or decarburising in their action, depending on the activating material used in the mixture and on the temperature of heat treatment. It is concluded that packing materials used to protect steel during heating operations are probably responsible for the skin softness of the steel after heat treatment.

Case-Carburising of Steel. H. B. Northrup. (Fuels and Furnaces, 1929, Vol. 7, Mar., pp. 347-352).

Depth and Character of Case Induced by Mixtures of Ferro-Alloys with Carburising Compounds. E. G. Mahin and R. C. Spencer.

(Transactions of the American Society for Steel Treating, 1929, Vol. 15, Jan., pp. 117-144). The experiments described in the paper show that if silicon absorption is confined to surface layers of iron or steel, carbon absorption during case carburisation may be retarded without materially affecting the rate of inward migration of the carbon after it has been absorbed. By utilising this principle it has been found possible to produce a deep case without a zone of free cementite, by using an ordinary carburiser in conjunction with ferro-silicon, and by employing higher carburising temperatures, thus shortening the time required to complete the case carburisation.

Case-Hardening of Steel in Cyanide Baths. F. Rapatz. (Stahl und Eisen, 1929, Vol. 49, Mar. 28, pp. 427-429). In molten cyanide salts the steel absorbs simultaneously both carbon and nitrogen. The author describes experiments made with the Durferit cyanide hardening flux, on a mild steel containing 0.12 per cent. carbon. After immersion for half an hour at a temperature of 850° C. the depth of case was 0.35 mm., at the end of 2 hr. it was 0.5 mm., and after 6 hr. it was 0.6 mm. At 950° the cementation proceeded a little more rapidly, the case reaching a depth of 0.6 mm. at the end of 2 hr., and this was not increased by longer immersion. At 850° after 2 hr. the nitrogen rose from nil to 0.9 per cent. at a depth of 0.05 mm., to 0.3 per cent. at a depth of 0.1 mm., and to 0.05 per cent. at a depth 0.6 mm. The carbon was 0.65, 0.5, and 0.32 per cent. at depths of 0.05, 0.3, and 0.6 mm. respectively. The case is readily capable of hardening, and the process appears of utility for case-hardening small parts.

Salt-Bath Hardening. (Automobile Engineer, 1929, Vol. 19, Jan., p. 16). A brief note on the use of Durferit hardening flux. A hooded furnace is used; tempering salt is first melted, and to this is added three times as much of the hardening flux. For ordinary steels the temperature is held at 950° C.; a case 0.02 in. thick is obtained in half an hour, or 0.04 in. thick in 2 hr. Tempering may be carried out by a short immersion in the same bath, if desired, though for routine work a second furnace held at, say, 760° C. is recommended. Freedom from distortion in the hardened parts is claimed. The consumption of the salts is said to be about 2 per cent. of the weight of the work treated.

The Cyanide Bath. V. E. Hillman. (Fuels and Furnaces, 1929, Vol. 7, Jan., pp. 31-34). The author discusses the various compounds that are used in making up the cyanide bath, their concentration and proper method of keeping them up to strength, the correct operating temperature, depth of case obtained, and the properties of the case and core.

Distortion in Case-Hardening. (Metallurgist, 1928, Vol. 4, Dec. 28, pp. 181-182). An abstract, with comments, of an article by R. Barat

(*Revue de Métallurgie, Mémoires*, 1928, Vol. 25, Oct., pp. 585-589; see *Journ. I. and S.I.*, 1928, No. II. p. 368).

The Differential Method for Measuring the Thickness of Hard Cases without Sectioning Them. E. G. Herbert and P. Whitaker. (Paper read before the Iron and Steel Institute, May 1929: this *Journal*, p. 561).

Note on Ehn's Cementation Test. R. Wasmuht and P. Oberhoffer. (*Stahl und Eisen*, 1929, Vol. 49, Jan. 17, pp. 74-77). Ehn has shown that it is possible to obtain by cementation a complete series of structures of steels that have undergone different degrees of deoxidation, and contain in consequence more or less non-metallic impurities. The examination of a series of different structures would be a means for showing how the steel had been made and deoxidised. The authors have now made an investigation of the structure of carburised steels that had been carefully deoxidised and of others not so carefully made. They find that the evidence afforded by the varying structure is not very clear as to the degree of deoxidation of the steel, as there are other factors which exercise a considerable influence on the structure, such as the mode of deoxidation and the structure and size of the inclusions.

Solubility of Carbon in Normal and Abnormal Steels. O. E. Harder and W. S. Johnson. (*Transactions of the American Society for Steel Treating*, 1929, Vol. 15, Jan., pp. 49-68). The present paper is a continuation of a study of normal and abnormal steels (*Ibid.*, Vol. 13, pp. 961-1008). In the present investigation a study has been made of the solubility of carbon in typical normal and abnormal steels, making use of longer carburising times and different carburising temperatures. Specimens were quenched from various temperatures, including the carburising temperature and lower temperatures, usually by 50° F. intervals, and the temperature at which the separation of the carbide first took place was noted. The results show that for a given carbon content precipitation takes place in the abnormal steel at a higher temperature. It was also found that as the carburising temperature increases the amount of carbon taken up by the normal and abnormal steels becomes essentially the same. The results seem to be consistent with the previously proposed mechanism of the formation of the characteristic microstructure found in abnormal steels.

Cause and Control of Abnormality in Case-Carburised Steel. V. N. Krivobok. (*Fuels and Furnaces*, 1928, Vol. 6, Nov., pp. 1553-1554, 1558).

The Nitrogenation of Special Steels. L. Guillet. (*Comptes Rendus*, 1927, Vol. 185, Oct. 24, pp. 818-821). It had been thought that

quenched and tempered steels, after nitrogenation (heating for 96 hr. in a current of ammonia gas), would show that special form of brittleness known as temper brittleness (*Kruppkrankheit*). Systematic researches have demonstrated the influence of molybdenum, and have given rise to the following conclusions: Chrome-aluminium steels are relatively little liable to temper brittleness; nickel-chrome-aluminium steels are very susceptible, while chrome-aluminium-molybdenum steels with little nickel are not. Nickel-chrome-aluminium-molybdenum steels are slightly susceptible, but they nevertheless have satisfactory properties. The 96-hr. treatment did not reduce the hardness of the specimens tested.

Surface Hardening of Steel with Nitrogen. F. L. Coonan. (Heat Treating and Forging, 1928, Vol. 14, Dec., pp. 1400-1401). The nitrogenation of steel and the composition of the metal are briefly discussed.

The Case-Hardening of Steels by Nitrogen. (Engineer, 1928, Vol. 146, Dec. 7, pp. 637-638). The "Nitration Process" of case-hardening is described, and the properties and characteristics of the special steels used (Nitr alloy steels) and of the cases produced are enumerated.

Nitrogen Hardening. (Automobile Engineer, 1929, Vol. 19, Mar., pp. 91-92).

A New Method of Nitrogen Case-Hardening. G. F. Bason. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 932-934). Collector rings on some electrical machinery, after service, were found to have become hardened in spots, and these spots caused sparking and pitting of the rings. The spots appeared to be glass hard, and seemed by their shape and by the spacing between them to have been transmitted to the rings from the brushes when the former were at a standstill. It is believed that this hardening may be due to the ring being bombarded with nitrogen ions, thereby nitrogenising the surface of the steel. It is suggested that this process be imitated as a possible means of evolving a practical method of nitrogenation superior to those at present in use.

Methods of Approximating Certain Physical Characteristics of Nitrided Steel Cases. G. M. Eaton. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Jan., pp. 1-35). It is shown that the vital characteristics of the case of nitrided articles are hardness and ductility. Photomicrographs are given showing the impressions produced on the nitrided case by practically all the recognised hardness testing machines. These impressions are briefly discussed, and the fact is brought out that the Vickers diamond hardness tester gives the clearest distinction between the brittle and ductile characteristics of nitrided cases.

Surface Hardening of Special Steels with Ammonia Gas Under Pressure. R. H. Hobrock. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Apr., pp. 543-568). Samples of special steels were nitrogenated with ammonia gas under pressure and the nature of the case examined. The results show that an increase in the pressure of the ammonia gas results in a decrease in the surface hardness, but greatly increases the depth of case produced in a given time. Curves are presented correlating hardness, time of treatment, and depth of case. From the results of these experiments and from the work of other investigators the author comes to the following conclusions: (1) An alloy intended for the establishment of a hard surface of no great depth might contain much more aluminium than an alloy intended for use where a deep case is required; (2) where high surface hardness and deep penetration are to be obtained by nitrogenation under pressure the amount of aluminium in solid solution in the alloy must be accurately controlled; (3) the increase in hardness due to the nitrogenation of the alloy steels is due in part to the formation of a network of crystals of iron nitrides, and in part to the formation of slip interference particles of aluminium (and other) nitrides.

HEAT TREATMENT OF IRON AND STEEL.

Principles of the Heat Treatment of Steel. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 893-926). The continuation of a series of articles giving an outline of the elementary principles of the heat treatment of steel. (See Journ. I. and S.I., 1928, No. II., p. 367.) The present instalment includes a selected bibliography of literature on the subject.

Heat-Treating Improves Physical Properties of Carbon and Alloy Steel Castings. J. E. Donnellan. (Foundry, 1929, Vol. 57, Mar. 15, pp. 238-242). The information presented in this article is abstracted from the Report of the American Society for Steel Treating, covering recommended practices for the heat treatment of carbon and alloy steel castings. The present article is supplemented with micrographs and other data.

Thermal Treatments. Practical Advice. Macrographic Tests. L. Persoz. (Aciers Spéciaux, 1928, Vol. 3, Dec., pp. 300-307). After a brief explanation of the various heat treatments, the author gives practical advice for carrying them out. He also describes various macrographic tests and the means of performing them.

Heat Treatment of Drop-Forgings. C. L. Foreman. (Fuels and Furnaces, 1929, Vol. 7, Apr., pp. 497-500). Particulars are given of

continuous gas-fired and oil-fired furnaces fitted with automatic temperature control apparatus for the heat treatment of gears and rough forgings.

Heat-Treating Parts for Airplane Manufacture. J. B. Nealey. (Iron Trade Review, 1928, Vol. 83, Oct. 11, pp. 899-900, 902). An outline is given of heat-treatment practice at the plant of the Mono-Aircraft Co., Moline, Illinois.

Tempering Changes in Steels. R. Hay and R. Higgins. (Journal of the Royal Technical College, Glasgow, 1929, Vol. 2, Part I., Jan., pp. 73-80). The study of tempering changes has been extended to alloy steels. The tempering of martensitic steels with increasing temperature has been found to give property-temperature curves of the form represented by the equation:

$$y_t = y_0 e^{-at},$$

where y_t is the property at temperature t , y_0 is the initial property value in the martensitic state, and a is a constant. A classification of iron alloys has been suggested, based on the thermodynamic equation:

$$-\Delta T = RT^2 (x_1 - x_2)/L,$$

where x_1 = concentration of solute in the high-temperature phase, and x_2 = the concentration of the solute in the low-temperature phase, and R , T , and L have the usual significance. By this method two classes of solute are obtained—namely, those which lower the δ - γ transformation and raise the γ - α transformation, such as silicon, chromium, vanadium, molybdenum, tungsten, &c., and those which act in the opposite manner by raising the δ - γ change and lowering the γ - α change, such as carbon, nickel, copper, and aluminium. The significance of this method is discussed, with special reference to the iron-carbon system, and it is pointed out that the eutectoid point is merely the intersection of the line SE representing the change in the solubility of iron carbide in γ -iron with the line representing the depression of the A_3 point by carbon.

On Some Properties of Quenched Steels. K. Tamaru. (Bulletin of the Institute of Physical and Chemical Research, 1928, Vol. 7, Oct., pp. 1028-2034). (In Japanese.) The magnetisation of cementite in different forms was measured, and it was found that the magnitude of the A_0 transformation of pearlite cementite was greater than that of globular cementite. A 0.9 per cent. carbon steel was quenched in water and tempered at 392° C. for various periods. If the time of tempering was short the separated cementite was fine, but its size increased with the time of tempering. The A_0 transformation was found to be large when the cementite particle was fine, and became small when the

latter grew. When a quenched high-carbon steel was tempered at a gradually increasing temperature two maxima of magnetisation were observable at 120° C. and 300° to 350° C. These are considered to be the same phenomenon, and to correspond to the decomposition of β martensite and the growth of minute cementite particles. The former results in the formation of ferrite and cementite and hence increases magnetisation. The growth of cementite particles decreases magnetisation. Carbon steels (0.9 per cent. C) were quenched and tempered, the temperature and the time of tempering being varied. The effect of tempering is shown to be complete in 15 min. at a temperature above 200°; quenched steels contracted up to 200°, then expanded to 260°, and again contracted above 260°. The first contraction corresponds to the decomposition of α to β martensite; the expansion to the decomposition of austenite to β through α martensite; the last contraction corresponds to the transformation of β martensite to troostite.

Effect of Quenching and Tempering on the Hardness and Impact Resistance of a High-Chromium-Silicon Steel. F. T. Sisco. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 859-865). The author gives the results of an investigation of quenching and tempering temperatures on an alloy steel containing 1.2 per cent. carbon, 1.2 per cent. silicon, and 18 per cent. chromium. The best quenching temperature was found to be 1800° to 1850° F. The steel retains its hardness at all temperatures below 1000° F. The Izod impact values are low and are but little affected by varying the tempering temperature.

Austenite Decomposition and Length Changes in Steel. E. C. Bain and W. S. N. Waring. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Jan., pp. 69-95). This paper, which is preliminary in character, discusses the continuous change in axial length of a number of steel cylinders occurring during quenching at various rates. The two steels studied were an oil-hardening die steel and a stainless steel. The equipment used for recording the length changes is described, and suggestions for its improvement are put forward. The changes in length of steel rods accompanying tempering and at liquid air temperatures are also presented. All these data, together with some magnetic measurements on the same steels, are considered from the viewpoint of their evidence regarding the behaviour of austenite during decomposition. The possibilities of the influence of quenching stresses on the proportion of martensite and austenite are discussed in particular. It is suggested that the method employed in measuring length-changes during quenching may be used in a practical way to evaluate the quenching efficiency of various quenching media. The curve of length-change plotted against time during quenching in a known medium gives some fundamental notion of the nature of the steel.

The Change of Specific Gravity of Cold-Worked Iron and Steel by Tempering. K. Tamaru. (Bulletin of the Institute of Physical and Chemical Research, Tokyo, 1929, Vol. 8, Mar., pp. 187-196). (In Japanese.) The temperature of strain-release for iron and steel was determined from the change in specific gravity, and was found to be 400° for all the specimens treated. Armco iron showed a maximum of density at 150° C. and a minimum at 400° C. The values of the maximum and the minimum decreased with the carbon content of the steel, disappearing finally at 0.2 per cent. of carbon. When a strained specimen is tempered at a low temperature, a minute increase in grain-size takes place, and hence the specific gravity increases to yield a maximum. If the tempering temperature is raised still higher, the interior of the grain separates into a series of thin layers, and increases the total surface of the grain, thus yielding a minimum density.

The Influence of Heat Treatment at Below A_1 on the Properties of Commercial Iron and Steel. W. Köster. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Feb., pp. 503-522). Heat treatment of ordinary steel at temperatures below A_1 has a marked influence on the properties. When a low-carbon steel is quenched from successively increased temperatures below the range at which the austenite breaks up, the elastic limit, the yield point, and the hardness are raised, while the elongation, contraction, bending number, resistance to torsion, the Erichsen drawing depth, the specific gravity, the electric conductivity, and speed of solution in acids are diminished. The changes in these properties begin to manifest themselves at 300° to 500° C. according to their sensitiveness to heat treatment, and the degree of variation rises rapidly with the quenching temperature. On quenching a steel in process of cooling down from different temperatures the same values are obtained as on quenching a steel that is being heated up. Thus the changes in the properties of a steel quenched from a point below A_1 are due to an equilibrium displacement within the steel. The capacity of a steel to improve with heat treatment below A_1 increases rapidly as the carbon rises to 0.6 per cent., but falls off as rapidly for a further increase in the carbon up to 0.9 per cent. The same condition affects the increase in the coercive force of a steel quenched after annealing at 250° .

Influence of Heat Treatment on the Quality of Tungsten Steel. W. Zietter. (Stahl und Eisen, 1929, Vol. 49, Apr. 18, pp. 521-526). For tungsten steels in general there are definite critical temperature ranges within which under sufficiently prolonged heating a separation out of tungsten carbide takes place, thus lowering the quality of the steel. Only in the case of tungsten steels with very low carbon, which anyhow are not of great utility on account of their low hardness, is there no separation of tungsten carbide. The formation of this carbide has no great influence, provided the tungsten and carbon contents are

correspondingly high, so that there may always remain the necessary amount of carbon in solution to produce a good hardening effect. The critical temperature range changes according to the chemical composition and must be determined for every group of alloy steels. In any case the tungsten steels should never be allowed to remain long within the critical range, and slow cooling from that range should be carefully avoided. A small addition of chromium, as is often used, is strongly to be recommended, since it makes the steel very much less susceptible to wrong heat treatment.

The Use of Temperature Gradients in Metallographic Studies. O. Tesche. (*Zeitschrift für technische Physik*, 1928, No. 10, pp. 419-422). By heating one end of a bar and keeping the other end cool, the author caused a temperature gradient to be set up in the bar; the specimen was quenched and examined microscopically. The structural changes where the temperature gradient passed through change points were clearly shown.

Heat Treatment and Testing of High-Speed Steel Tools. F. Rapatz. (*Stahl und Eisen*, 1929, Vol. 49, Feb. 21, pp. 250-255). The most suitable heat treatment and structure for twist drills, cutters, and reamers are discussed, and results of tests with such tools are reported. The steels chosen for the experiments were: a chromium-cobalt steel containing carbon 1.5, chromium 12, and cobalt 2 per cent.; and a tungsten-vanadium steel, with tungsten 18 and vanadium 1.5 per cent. The most suitable microstructure for such tools is the same as that found suitable in lathe tools, and it is obtained by hardening at 1280° to 1320° C. and annealing at 550° to 600° C. At such high hardening temperatures it is difficult to prevent fusion of the cutting edges or surface decarburisation. A barium chloride bath does not prevent this, but a borax salt bath can be used with satisfaction, though borax has the disadvantage that it attacks the lining and electrodes of the bath more strongly. The tool should cool to 150° before annealing, and in order to allow time for the austenite to change to martensite the annealing period should be 15 min. to 2 hr., according to the composition and size of the piece. The hardness is tested either with the file, the Rockwell hardness testing machine, or by microscopic examination. Electric resistance methods can be used, but only with advantage in the case of mass production.

A New Method for Heat-Treating High-Speed Steel. H. C. Knerr. (*Transactions of the American Society for Steel Treating*, 1929, Vol. 15, Mar., pp. 429-450). In the method described a high-frequency induction furnace is used. The chief features include close temperature control, the use of a salt bath which does not give off fumes or attack the tools, prolonged container life, absence of furnace deterioration, comfortable working conditions, low heating cost per pound of steel, and

the ability to employ full hardening temperatures (in the neighbourhood of 2400° F.) without injury to finished surfaces or cutting edges of high-speed steel tools.

Heating High-Speed Steel to 2400° F. in Molten Lead. W. C. Searle. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 927-931). The author describes the apparatus and method of heating high-speed steel to 2300° to 2400° F. in molten lead. Photomicrographs show the structure obtained in specimens at 2200°, 2300°, and 2400° F.

Some Modern Methods of Hardening Steel. A. R. Page. (Drop-Forger, 1929, Vol. 9, May, pp. 16-32). The Wild-Barfield and the "hump" methods of hardening are described, and particulars are given of their operating costs.

The Quenching of Steel by Means of the Wild-Barfield Electro-Magnetic Furnace. (Génie Civil, 1929, Vol. 94, Apr. 6, pp. 336-338). The basic principle on which the Wild-Barfield furnace works is explained, the furnace is described, and the advantages obtained in the material quenched after heating in it are enumerated.

The Quenching of Steel. P. J. Haler. (Engineering, 1929, Vol. 127, Jan. 4, pp. 25-26). The author discusses the question of the abstraction of heat from a highly heated body as it occurs in the quenching of steel in a liquid. He deals with the rate at which the steel is plunged into the quenching medium, and the influence of this factor on the disturbance and displacement of the envelope of steam by which the body is surrounded. He records experiments on the change of dimension of bodies of various shapes when plunged in different ways.

Quenching and Work-Hardening. L. Grenet. (Aciers Spéciaux, 1928, Vol. 3, Dec., pp. 293-299). The mechanisms of hardening by quenching and of work-hardening are discussed and compared.

Surface Cooling of Steels in Quenching. H. J. French, G. S. Cook, and T. E. Hall. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Feb., pp. 217-288). The authors have made a study of the surface cooling of steel spheres when quenched in water, sodium hydroxide solutions, oils, or cooled in air. The characteristics of the cooling curves are described, and the effects of some of the variables encountered in commercial heat treatment upon the cooling of steel bodies are discussed. These variables include mass, oxidation, and smoothness of the surface, relation of the character of the surface to the coolant, manner of circulation of the coolant, and gases formed by or released from the coolant. Centre and surface cooling curves obtained for pressure spray quenching with water are correlated with the tensile and impact properties obtained in low-carbon steels, ingot iron, and

wrought iron. Comparisons are also made between experimental cooling curves and cooling curves derived from two different sets of assumptions.

The Use of Mineral Oils in the Heat Treatment of Steels. L. Roy. (*Aciers Spéciaux*, 1929, Vol. 4, Feb., pp. 75-77). The first of a series of articles dealing with the use of oils for quenching and tempering. In the present instalment characteristics of oils are enumerated.

Short Account of the Production of the First Batch of Sorbite Rails on the Commercial Scale at the Nadeshdinsk Works. N. V. Kolokoloff. (*Journal of the Russian Metallurgical Society*, 1928, No. 3, pp. 107-118). (In Russian.)

Method of Sorbitisation of Rails used at Nadeshdinsk Iron and Steel Works, Ural. N. N. Shadrin. (*Journal of the Russian Metallurgical Society*, 1929, No. 1, pp. 83-95). (In Russian.)

The Annealing of Cast Iron. H. H. Beeny. (Paper read before the Institute of British Foundrymen, Mar. 14, 1929: *Foundry Trade Journal*, 1929, Vol. 40, Mar. 28, pp. 229-231; Apr. 4, pp. 251-253). The author describes the results of an investigation of the influence of annealing on cast iron. At annealing temperatures immediately below 800° C. the pearlitic carbide is unstable and its destruction is merely a matter of time, but is the more rapid the higher the silicon in the iron. Massive carbide as found in chilled metal requires a temperature of approximately 850° C. to break it down completely in a 2- or 3-hr. period. In general, the pearlitic carbon is stable at a temperature of over approximately 800° C., and complete annealing cannot, therefore, be accomplished in this range of temperature alone. The statement must be qualified, in that the higher the silicon the less is the combined carbon retained, until with a silicon of 3.0 per cent. it becomes almost completely unstable. In medium and low silicon irons reheating above 800° C. will re-form a proportion of the carbide, the amount of carbide remaining stable or re-formed increases with temperature from 800° up to at least 950° C. The decomposition of carbide is rapid in the range below 800° C., so that the amount of carbide in the cold metal depends upon the rate of cooling through this range. Thus cooling in air blast retains considerably more carbide than cooling in still air. Pearlitic carbon has a definitely beneficial action on the transverse and tensile strength of cast iron. The machinability is increased by loss of combined carbon. To obtain maximum machinability, castings should first be annealed at 850° C. to remove possible chill and equalise the combined carbon in all parts, and then (actually or by very slow cooling) be maintained below 800° C. to remove all combined carbon. This gives the minimum Brinell hardness. When all the combined carbon has been removed by full annealing it is found that the Brinell hardness

increases proportionately with the silicon content. The Brinell hardness increases with the combined carbon in any one metal, but the hardening action of silicon is so marked that the Brinell hardness gives no idea of the combined carbon, irrespective of grade of metal, nor does it give the slightest indication of tensile or transverse strength.

Service Annealing of Sling and Crane Chains. W. J. Merten. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Feb., pp. 193-216). The author discusses the inconsistent results in tests for ductility and strength that are ordinarily obtained when chains are annealed at temperatures unsuited for links that have been severely deformed and cold-worked in service. A uniform recrystallisation at temperatures considerably above the transformation range is recommended to render the chain entirely safe for further service without resorting to a reduction of the safety load, and basing the calculation of permissible stresses on the average cross-sectional dimensions only.

Technological Study of the Bright Annealing of Steel in the Electric Furnace. A. Pomp and L. Walther. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1929, Vol. 11, pp. 15-30). The construction and operation of a 25-kw. electric bright annealing furnace in the Kaiser-Wilhelm-Institut is described. No decarburisation of steel occurred up to 700° C. when hydrogen was used as the protecting gas. On the other hand, when town gas was used partial decarburisation began at 600° C. By annealing in the electric furnace, the properties of deep-drawing strip steel were improved in comparison with those of material treated in a coal-fired pot annealing furnace, owing to the better control over the heat distribution, the temperature, and the duration of annealing; decarburisation by the use of hydrogen as the protecting gas only occurred when the carbon content of the material was not too low. Tests showed that the hydrogen-filled electric furnace was suitable for recrystallisation anneals. Transformer and dynamo sheets annealed in hydrogen gave better watt-loss values than sheets annealed in a continuous furnace. In preparing cold-rolled dynamo band steel, critical deformation and annealing, the coarsest possible grain-size, and uniform structure are factors leading to the most satisfactory watt-loss values.

Vacuum-Annealing of Metals. L. Guillet and A. Roux. (Revue de Métallurgie, Mémoires, 1929, Vol. 26, Jan., pp. 1-11). The authors describe their apparatus used for annealing specimens *in vacuo*, and tabulate their results obtained in investigating the occluded gases which were liberated by the vacuum anneal.

The Pickling and Annealing of Tubes. (Röhrenindustrie, 1929, Vol. 22, Jan. 17, pp. 21-22). The theory and practice of the pickling and annealing of tubes is discussed.

WELDING.

Autogenous and Electric Welding in Steel and Iron Foundries. H. Neese. (*Giesserei Zeitung*, 1929, Vol. 26, Apr. 15, pp. 209-216).

Metallic Electrodes for Cast-Iron Arc Welding. S. Satoh. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 162). Various mixtures of graphite and carborundum were coated on wrought-iron bars, and a series of cast irons, from grey to white, was deposited by using the coated bars as electrodes. Chemical analyses, hardness tests, and microscopic examinations of the deposits were made, and three kinds of electrodes were selected as suitable for grey cast-iron welding. The optimum quantities of the coating for the bars were determined, and tests were made of the effect on welding of adding calcined borax, calcium carbonate, and barium carbonate to the coating mixtures and also by changing the polarity. It was found that the fusion of the electrode could be retarded by adding barium carbonate to the coating that cover the electrode and by connecting this electrode to the negative pole of the generator.

New Applications of the Electric Welding Process. J. Sauer. (*Röhrenindustrie*, 1928, Vol. 21, Dec. 20, pp. 514-515).

The Applications of Electric Arc Welding. M. Lebrun. (*Arts et Métiers*, 1929, Vol. 82, Mar., pp. 87-102; Apr., pp. 140-148). The author gives examples of the application of electric welding to the building of various structures.

Welding Costs are Reduced by Use of Larger Electrodes. C. J. Bowers. (*Iron Trade Review*, 1928, Vol. 83, Dec. 20, pp. 1564-1565). The author presents the results of time studies made to determine the value of the use of larger welding electrodes. The use of larger electrodes has been materially retarded owing to the fact that many machines are in operation whose maximum amperage capacity will not permit the use of the larger electrodes. The savings which can be effected by the use of larger-sized welding wire will help considerably to pay for the installation of welding machines of larger capacity.

Control of Welds by Magnetic Patterns. A. Roux. (*Comptes Rendus*, 1927, Vol. 185, Oct. 24, pp. 859-861). The poles of an electromagnet are applied to one side of the steel test-pieces, symmetrically with regard to the line of the weld; the current is switched on to the magnet, and iron filings are dusted on to a sheet of paper laid on the other side of the specimens. If the weld is sound, the pattern made by the filings ("magnetic pattern") is normal; any discontinuity within the metal at right angles to the magnetic field is indicated by an accumulation of filings perpendicular to the regular lines of the pattern.

Automatic Arc Welding Machines. F. Niethammer. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Feb. 16, pp. 209-219). A large variety of automatic arc welding machines are described and illustrated. The author considers that these machines, as substitutes for riveting in mass production, represent a great advance.

Electricity Applied to Welding of Metals. A. N. Otis and W. L. Warner. (Paper read before the Western Metals Congress, 1929: *Heat Treating and Forging*, 1929, Vol. 15, Mar., pp. 326-327).

Automatic Welding of Rolled Steel Plates and Sections. A. N. Otis and W. L. Warner. (*Rolling-Mill Journal*, 1929, Vol. 3, Apr., pp. 171-173).

Electric Welding in Iron Structures. S. Bryla. (*Zeitschrift des Oesterreichischer Ingenieur- und Architekten-Vereines*, 1928, Vol. 80, Sept. 21, pp. 328-333).

All-Welded Petrol Storage Tanks. (*Engineer*, 1928, Vol. 146, Dec. 21, p. 696). The construction of eleven petrol storage tanks by the Commonwealth Oil Refinery Co. of Australia is described. The bottoms were erected complete on the ground before the structures of the tanks were begun. Six wedge-shaped wooden frames, long enough to accommodate the width of two plates and spaced about 10 ft. apart, were built. These frames allowed access to the joints from underneath; after welding they were pulled aside, and the plates fell into position on the sand.

Mass Production Welding Operation. J. W. Meadowcroft. (Paper read before the American Welding Society, Oct. 9, 1929: *Iron Age*, 1928, Vol. 122, Nov. 8, pp. 1154-1156). The author discusses the welding of automobile parts, pointing out the extended use of spot- and flash-welding machines.

Autogenous Welding with Town Gas. A. Müller and B. Bibus. (*Gas- und Wasserfach*, 1928, Vol. 71, June 9, pp. 566-569). To determine whether town gas was economical in use for welding, the following characteristics of a number of gases were examined: The flame temperature, the available calorific power, the velocity on leaving the burner, the ratio of the fuel gas to the oxygen supply, and the chemical action. It was concluded that town gas could completely replace hydrogen, but acetylene only in part, for welding and cutting purposes, and could be profitably employed for certain other purposes, such as preheating work.

The Construction of Pipe Lines and Gas Welding. (*Röhrenindustrie*, 1929, Vol. 22, Jan. 3, p. 7). The advantages of gas welding in making

the joints of long pipe lines are discussed ; various methods of making the joints are illustrated. The application of gas welding to the manufacture of tubular objects, such as superheaters, &c., is also dealt with.

Oxy-Acetylene Welding by Machine. J. L. Anderson. (Paper read before the International Acetylene Association, Dec. 15, 1928 : *Iron Age*, 1929, Vol. 123, Feb. 28, pp. 591-595). The author reviews recent developments in the design of oxy-acetylene welding machines. Mechanical welding is now used successfully on steel plate up to $\frac{3}{8}$ in. thick. With torches consuming 3.3 cu. ft. of oxygen and 3.2 cu. ft. of acetylene a minute plain butt welds can be made in $\frac{1}{4}$ -in. steel plate at the rate of 24 in. a minute, and in $\frac{3}{8}$ -in. plate at 11 in. a minute. In the welding of heavy sheet metal the best results may be obtained by using two blow-pipes, one below and the other above the plate. In good practice more than half the heat is generated by the lower torch. On 14 gauge and thinner sheets satisfactory joints are made with the flame on the upper surface of the seam only.

Fabricates Welded Steel Railroad Ties on Production Basis. H. R. Simonds. (*Iron Trade Review*, 1929, Vol. 84, Mar. 28, pp. 843-845). Particulars are given of the apparatus and methods employed by the Delaware and Hudson Railroad for the manufacture of welded railroad ties. The automatic arc welding machine used has a capacity of 70 ties a day.

Allowable Stresses in Welded Structures. S. W. Miller. (Paper read before the American Welding Society, 1928 : *Heat Treating and Forging*, 1928, Vol. 14, Dec., pp. 1402-1404, 1431 ; *Iron Trade Review*, 1929, Vol. 84, Feb. 14, pp. 464-466). The maximum working stresses permissible in welded work are discussed. Kinzel's formula,

$$S = \frac{T}{7.15} \sqrt{\frac{s}{E}}$$

where S is the permissible working fibre stress, T the ultimate tensile strength, and E the percentage elongation as determined by a bend test, is explained.

Brazing in an Atmosphere of Hydrogen. B. S. Havens. (*Heat Treating and Forging*, 1929, Vol. 15, Mar., pp. 349-350). A brief description of a gas-filled electric brazing furnace and of the automatic charging and discharging gear. The gas is a mixture of hydrogen and nitrogen.

Latest Investigations of Welds by X-Rays. A. Herr. (*Zeitschrift des Vereines deutscher Ingenieure*, 1928, Vol. 72, Nov. 17, pp. 1671-1678).

Tests on Full-Size Pipe Joints. (Iron Age, 1929, Vol. 123, Feb. 7, pp. 407-408). The results are published of tests on welded joints in full-size pipes. Both low-carbon lap-welded pipe and seamless steel pipe were used in sizes from 4 to 16 in. diam. Four types of joints were tested—namely, butt-welded, commonly used for oil transport lines, and three variations of the socket joint which have been specified on power-house work. Dimensions of the welds tested are shown. The welding rod used was a mild steel containing enough silicon and manganese to be self-fluxing. The results show the butt weld to be the strongest.

MISCELLANEOUS PRODUCTS.

The Manufacture of Iron and Steel Tubes. J. Mitchell. (Journal of the West of Scotland Iron and Steel Institute, 1929, Vol. 36, Jan., pp. 48-55). An outline is given of the manufacture of both welded and weldless tubes.

Tubes in Steam-Turbine Construction. (Röhrenindustrie, 1928, Vol. 21, Dec. 6, pp. 499-501). The various parts of steam-turbines, for the construction of which tubes are used, are enumerated, and some of the properties required in the materials of which the tubes are constructed are mentioned.

Chain Steel Requires Special Qualities. J. R. Miller. (Iron Age, 1929, Vol. 123, May 2, p. 1205). An outline is given of American practice in the manufacture of welded steel chain. Basic open-hearth steel is preferred to Bessemer steel owing to the tendency of the latter to cold-shortness. The chemical composition of the steel is: Carbon 0.09, phosphorus 0.025, manganese 0.32 to 0.45, and sulphur 0.045 per cent. After forming and shearing, the individual links are brought up to welding heat and welded by quick hammer-blows, sometimes under a flat die and sometimes a shaped die. The finished chain is normalised at about 1650° F.

The Manufacture of Riveted Drums for Large Boilers. (Engineering, 1928, Vol. 126, Dec. 7, pp. 722-724). **Drop-Link Chain Grate Stoker.** (Ibid., 1928, Vol. 126, Dec. 28, p. 825). **A Visit to the Renfrew Works of Babcock and Wilcox.** (Engineer, 1928, Vol. 146, Dec. 7, pp. 628-630, 632). Plant for the manufacture of boilers and of chain-grate stokers is illustrated and described.

Alloy Steels Assume Important Rôle in Manufacture of Airplanes. E. Joyce. (Iron Trade Review, 1928, Vol. 83, Dec. 13, pp. 1491-1493, 1495). Alloy steel is used principally in the form of thin-walled tubing. The use of chrome-molybdenum steel is rapidly increasing in airplane

construction, and the steel used in America contains carbon 0.25 to 0.35, chrome 0.80 to 1.10, molybdenum 0.15 to 0.25 per cent. Most of this steel is purchased in the normalised condition in the form of thin-walled tubing, and is welded directly into structural units either by the oxy-acetylene or electric arc methods without further heat treatment. Another steel of importance is a 3.5 per cent. nickel alloy, which is used largely in the production of heat-treated members requiring high strength and good ductility, such as bolts and pins. Another class of alloys which have distinct possibilities for aircraft construction comprises the so-called stainless irons and stainless steels.

Steel Sleepers. (Engineer, 1928, Vol. 146, Dec. 14, p. 666). A drawing shows the design of the Sandberg steel sleeper, which the Southern Railway has adopted for use on their system. The sleeper is in one piece of compressed steel $\frac{5}{16}$ in. thick, strengthened by a rib in the centre along the whole length. On the underside, at $2\frac{1}{8}\frac{1}{2}$ in. on each side of the centre line, it is further strengthened by two ribs $\frac{3}{16}$ in. to $\frac{3}{4}$ in. thick. To obtain the necessary length for the inner and outer jaws, which are pressed upwards, the metal forming them is "joggle" cut. The inner jaw embodies the upper strengthening rib up to its top; the outer jaw consists only, at the top, of the main portion of the thickness of the main plate. The outer jaw is shaped at such an angle that when the wooden key—which differs in form from the ordinary key—is driven in, the rail and base plate are tightened on to the sleeper. Thus the inner, or gauge, jaw is the stronger, and even if the keys are driven excessively it is the outer jaw that springs whilst the inner maintains the correct gauge. The base plate is also of pressed steel, and so shaped on the upper side as to give the inclination of 1 in 20 to the rail.

The Saw. C. Frémont. (Bulletin de la Société d'Encouragement pour l'Industrie Nationale, 1928, Vol. 127, July–Aug.–Sept., pp. 643–720). The author devotes a considerable amount of space to a history of the development of the saw from the earliest times. He then discusses the saw marks made on the cut surfaces of the article sawn; he describes a hand-saw fitted with a dynamometer and the results of his experiments made to determine the work done during sawing, and the effects on it caused by changes of the conditions of operation. He then deals with the blade of the saw, and with various matters affecting it.

Drill Bits Faced with Hard Metals. (Iron Age, 1929, Vol. 123, Apr. 18, pp. 1065–1066). The use of stellite and tungsten carbides for facing drilling tools is discussed.

Metallurgical Problems of Transmission Gears. E. F. Davis. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 831–858). The author deals chiefly with the metallurgical

phases in the production of gears, and reviews the contributing factors toward the success or failure of the final product. A brief description is given of the modern installations used in the gear industry, and the advantages and disadvantages of different methods of heat-treating gears are pointed out.

PICKLING.

The Influence of Pickling Operations on the Properties of Steel. H. Sutton. (Paper read before the Iron and Steel Institute, May 1929 : this Journal, p. 179).

Sheet Pickling Machines. W. Krämer. (Stahl und Eisen, 1928, Vol. 48, Nov. 8, pp. 1570–1577). A discussion of various methods of carrying out the pickling process, with illustrated descriptions of tanks and machinery for dipping and jiggling the cages containing the sheets. The removal of the vapours, washing and drying the sheets, and neutralisation of the waste liquors are also discussed. An abridged translation of this paper appears in Iron and Coal Trades Review, 1928, Vol. 117, Dec. 14, pp. 865–866 ; Dec. 21, p. 906.

Investigations into the Pickling of Low-Carbon Steel Sheets. P. Bardenheuer and G. Thanheiser. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 322–342). The results of microscopic investigations of pickling blisters are described, and support is found for the opinion that they are due to accumulations of hydrogen in the material. The influence of the strength of the sheet, pickling temperature, nature and concentration of the acid, and addition of Vogel's pickling agent on the diffusion of the hydrogen were investigated. With rising temperature the amounts of hydrogen generated and diffused increased, but the ratio of the latter to the former decreased. At higher temperatures the addition agent lost some of its protective power. The diffused and liberated hydrogen increased with the concentration of the sulphuric acid up to 700 gm. H_2SO_4 per litre, and then fell off, the ratio of the diffused hydrogen to that liberated decreasing all through. In hydrochloric acid the amount of hydrogen evolved increased with the concentration, but the diffused hydrogen decreased. The greatest tendency towards the formation of pickling blisters was found in materials containing segregations or blowholes ; for this reason sheets from the head of an ingot were more susceptible than others from the bottom. High rolling temperature is a partial cure for this trouble ; material which is prone to develop blisters should be pickled under conditions permitting the minimum diffusion of hydrogen—namely, by using more concentrated acids, preferably hydrochloric acid, by applying heat, and by adding a protecting agent.

Pickling Sheets with Sulphuric Acid before Galvanising. H. Bablik. (Iron and Coal Trades Review, 1928, Vol. 117, Nov. 16, pp. 732-733). The advantages of sulphuric acid as compared with hydrochloric acid for the pickling of sheets are discussed. The chief advantage from a chemical point of view in the use of sulphuric acid for pickling in galvanising is that there is a much smaller consumption of the acid; where the consumption of hydrochloric acid amounts to 10 per cent. of the weight of the material pickled, a consumption of from 3 to 4 per cent. of sulphuric acid is to be expected. There is also a great gain in the pickling time, and with sulphuric acid it is possible to pickle at a much higher temperature than with hydrochloric acid. Some important factors to be observed in the use of sulphuric acid are dealt with.

COATING OF METALS.

(For Corrosion of Metals, see p. 813.)

Degasifying Process Facilitates Thick Impervious Plating. F. M. Dorsey. (Iron Trade Review, 1929, Vol. 84, Apr. 11, pp. 987-989; May 2, pp. 1182-1185). The author describes the commercial development of a process for the degasification of metals and their subsequent plating for the production of a protective metal film.

Measurements of Hydrogen Ion Concentration in Plating Baths. R. E. Brewer and G. H. Montillon. (Paper read before the American Electrochemical Society, May 1929).

Electrolytic Deposits of Metals. J. Roudnick. (Revue Universelle des Mines, 1928, Vol. 20, Dec. 1, pp. 237-243). The conclusion of a previous article (*see* Journ. I. and S.I., 1928, No. II. p. 377). In the present instalment the author discusses the technique of chromium plating under the headings: Preparation of articles; mounting; immersion in the bath; length of stay in the bath; finishing; and removal of gas. A note is appended in which solutions suitable for removing defective coatings from various bare metals are described; a useful table of defects, their cause and correction, is also added.

Mechanical Applications of Chromium Plating. W. Blum. (Mechanical Engineering, 1928, Vol. 50, Dec., pp. 927-930). After giving particulars of the physical properties of chromium (hardness, thermal expansion, density, melting point, electrical conductivity, adherence) the author discusses the uses to which chromium plating has been put on account of its resistance to wear: gauges and other measuring devices; various kinds of dies; rolls for forming metals; cutting tools for metal; bearing surfaces, &c. He shows the double saving obtained due to

longer life of the tools and parts and to the reduced stoppage of machines for their replacement.

A Survey of the Published Information on Chromium Plating. G. E. Gardam. (Paper read before the Electroplaters' and Depositors' Technical Society : *abstract*, Metallurgist, 1929, May, pp. 75-76)

A Study of Chromium Plating. R. Schneidewind. (University of Michigan, Engineering Research, 1928, Bulletin No. 10 ; Iron Age, 1929, Vol. 123, Mar. 7, pp. 670-672). A non-technical account is given of electro-deposited chromium and the commercial methods for its preparation.

Chrome Plating Progress Continues. W. M. Phillips and M. F. Macaulay. (Paper read before the Society of Automotive Engineers, Jan. 1929 : Iron Age, 1929, Vol. 123, Jan. 24, pp. 269-271). Recent advancements in chromium plating practice are discussed. Temperature and current density conditions are important factors in obtaining a bright plate. Considerable experimental work indicates that the type of steel best suited as an anode is one of low carbon content fully annealed. Alloy steels such as silicon and chromium steels are soluble and therefore are not so satisfactory.

Theory of the Electrolytic Deposition of Chromium from Aqueous Solutions of Chromic Acid. H. Gernet and V. Schischkin. (Zeitschrift für Elektrochemie, 1928, Vol. 34, Feb., pp. 57-62).

The Bent Cathode Test for Determining the Optimum Ratio of Chromic Acid to Sulphate in Chromium-Plating Baths. W. L. Pinner and E. M. Baker. (Paper read before the American Electrochemical Society, May 1929). The control of the ratio of chromic acid to sulphate is most important in the operation of chromium-plating baths. A rapid method of determining the proper quantity of either sulphuric acid or chromic acid, as the case may be, to be added to a bath to produce maximum throwing power is described. This method does not require a quantitative analysis of the solution of sulphate. The method was used to study the effect of chromic acid concentration on the permissible range of ratio of chromic acid to sulphate. The effects on permissible sulphate ratio of trivalent chromium and also of iron in a 2.5 molar chromic acid bath were also studied. Some qualitative observations on throwing power are reported.

The Electroplating of Cadmium from Cyanide Baths. L. R. Westbrook. (Paper read before the American Electrochemical Society, May 1929). The cyanide bath for commercial cadmium plating is discussed in detail from the standpoint of bath composition, including

the effects of variations in the concentrations of the different constituents on the electrical properties of the bath, such as cathode efficiency, conductivity, throwing power, electrode polarisation, anode corrosion and operating range of cathode current densities for satisfactory deposits. The effects of the presence of small amounts of other metals in the bath are considered, especially the marked improvement in the physical characteristics of the deposit resulting from the presence of a few hundredths of 1 per cent. of nickel, or larger amounts of cobalt or copper in the bath. The organic addition agents which function best with these baths are listed, and formulæ for typical baths are given.

Electro-Deposition of Cadmium for Rust Prevention. S. Wernick. (Paper read before the Electroplaters' and Depositors' Technical Society : *abstract*, *Metallurgist*, 1929, Mar., pp. 36-38).

Cadmium Plating. G. de Lattre. (*Revue de Métallurgie, Mémoires*, 1928, Vol. 25, Nov., pp. 630-636 : *abstract*, *Metallurgist*, 1929, Mar., pp. 41-42).

The New Methods of Nickel Plating at the Renault Motor-Car Works (*Aciers Spéciaux*, 1929, Vol. 4, Feb., pp. 78-82).

The Penetration of Hydrogen into Metal Cathodes and its Effect upon the Tensile Properties of Metals and their Resistance to Repeated Stresses ; with a Note on the Effect of Non-Electrolytic Baths and Nickel Plating on these Properties. F. C. Lea. (Proceedings of the Royal Society, 1929, (A), Vol. 123, pp. 171-185). The experiments described include static tensile and single-blow impact tests, repeated stress experiments in torsion and under direct stress, of specimens in acid and alkali baths, both with and without a current flowing, and also some tests on nickel-plated specimens. The materials tested were a mild steel (C 0.14, Mn 0.68, Si 0.19, S 0.04, and P 0.045 per cent.), the same metal nickel-plated, commercially pure nickel (over 99 per cent.), 70:30 brass, and rustless steel with about 26 per cent. of nickel and chromium. The results show that hydrogen penetrates the crystal boundaries of mild steel, nickel, and alloys rich in nickel and chromium, but the penetration does not affect the tensile strength or resistance to repeated stress : it affects, however, the elongation of the mild steel, but does not diminish the resistance of Izod mild steel specimens to single blows. Nickel plating has no effect on the tensile strength of mild steel, but considerably reduces the resistance to repeated stresses. Polishing the mild steel either prevents the hydrogen penetration between the crystals or modifies its action, but acid corrosion affects the surface considerably and accordingly reduces the resistance to torsional stresses. A caustic solution, with or without the presence of hydrogen, protects the specimen, and the fatigue range is raised.

European Hot Sheet Galvanising. H. Bablik. (Iron Age, 1929, Vol. 123, Mar. 21, pp. 811-812). **Acids Used in Galvanising Work.** (Ibid., Mar. 28, pp. 879-880). Two articles describing the galvanising of sheets as carried out in Central Europe. The sheets are pickled in a highly concentrated hydrochloric acid pickling bath, after which they are washed in water and dipped in a highly concentrated warm solution of zinc chloride, which covers the sheets with a layer of zinc chloride. The sheets are then dried and dipped into the zinc bath, where they remain as short a time as possible. The zinc bath contains an addition of aluminium. Sheets thus galvanised are ready without the necessity of artificial cooling. The zinc chloride solution provides far better adhesion of the zinc than when a flux is used. The pickling action of highly concentrated hydrochloric acid is explained in the second article.

Principles of Combustion as Applied to the Galvanising Furnace. W. G. Imhoff. (Fuels and Furnaces, 1929, Vol. 7, Mar., pp. 407-411). The first of a series of articles in which the author sets forth the basic principles of combustion as applied to galvanising furnaces.

What is Dross in Galvanising Pots. W. G. Imhoff. (Iron Age, 1929, Vol. 123, Feb. 21, pp. 536-538). The author discusses the various sources of dross production in galvanising, and methods for its limitation. The importance of using large pickling tanks to reduce the amount of dross is shown.

The Electro-Galvanising of Wire and Strip. A. C. J. Charlier. (Metal Industry, 1928, Vol. 33, Dec. 14, pp. 557-558).

White Spots on Zinc Coatings. W. G. Imhoff. (Iron Trade Review, 1929, Vol. 84, May 2, pp. 1179-1181). The author discusses the causes of the occurrence of white spots on zinc coatings, and means for their prevention. The various causes are summarised as follows: (1) quality of the zinc in the pot; (2) too high a temperature of the zinc bath; (3) too long a submersion time; (4) the gauge of the steel base being too light for the heat carried; (5) the withdrawal speed too fast; (6) low quality, hard, oxidised steel; (7) shortage of aluminium in the bath.

Durability and Defects in Galvanised Fittings and Tubes. E. Schreiber. (Röhrenindustrie, 1929, Vol. 22, May 23, pp. 163-164). The durability of zinc coatings, and defects which occur in them and the remedies, are discussed.

Studies on Sherardising. M. Kuroda. (Bulletin of the Institute of Physical and Chemical Research, Tokyo, 1929, Vol. 8, Jan., pp. 12-18). (In Japanese.) The influences of time and temperature upon sherardising were studied. When sherardising is carried out statically

the oxidation is harmless, either to the powder or to the product. The layer of powder becomes cindery only to a depth of a few mm., beyond which the oxidation does not proceed further, the product having a brilliant silvery lustre. It is considered best to apply heat at a temperature between 370° and 380° during 30 min. The tensile strength, elongation, hardness, and toughness are not greatly affected by this heating.

Has Tinplate a New Competitor? C. L. Mantell. (Iron Age, 1928, Vol. 122, Dec. 20, pp. 1555-1556). Investigations have been carried out in Germany on the use of aluminium-plate as a substitute for tinplate, with a result that drawn aluminium-plate was found to be well suited for food containers and, compared with tinplate, was very slightly attacked by the foodstuffs. Several plants for the production of aluminium-coated sheets are contemplated in Germany. Sheet steel coated with aluminium by a mechanical sweating or welding method has been produced previously. The aluminium layer is relatively thick, and material of this kind has shown high resistance to accelerated corrosion tests. Success in hot dipping of iron in aluminium is attained with difficulty and only after special preparation of the surface of the iron. Much of the difficulty is to be attributed to the tightly adhering film of aluminium oxide, which forms very rapidly, as well as to the occurrence of a large amount of iron-aluminium compounds. When iron is coated with aluminium, either by hot dipping or by mechanical rolling methods, there is a rapid alloying action between the two metals. This usually results in a very brittle layer adjacent to the steel or iron base. The uses to which such material could be put would be limited to those which do not involve bending or any other form of severe deformation.

Control of Temperature is Factor in Applying Lead Coating. W. G. Imhoff. (Iron Trade Review, 1928, Vol. 83, Dec. 20, pp. 1558-1559). A brief discussion of some of the points to be observed in the lead coating of iron and steel products. Tests have shown that it is impracticable to work with a bath of pure molten lead, owing to the difficulty of securing a uniform coating. By adding about 9 per cent. of tin to the bath the metal becomes more fluid and thinner and turns a lighter colour. A thoroughly saturated solution of zinc chloride with a small amount of fresh ammonium chloride is used as a flux. The temperature of the bath is held at about 650° F. The work is withdrawn from the bath at a speed which will allow all excess metal to drain off, and after the coating is set is cooled in water. If allowed to cool in air before dipping in water the lead becomes spongy, and oxidation sets in and spoils the coating.

Sprayed Metal Coatings. G. Kutscher. (Paper read before the Technical Trades Conference, Leipzig: Röhrenindustrie, 1929, Vol. 22, May 23, pp. 166-167).

Protective Paints. A. H. D. Markwick. (Institution of Civil Engineers, 1928: Selected Engineering Paper No. 59). Developments in paint technology are discussed. A portion of the paper deals with the corrosion and protection of iron and steel.

The Protection of Stocks of Iron Against Rust. D. F. Schott. (Glückauf, 1929, Vol. 65, Mar. 2, pp. 307-308). The author comments on the large amount of waste that must occur, particularly in large works, owing to the rusting of bars, rods, screws, &c., which must be either reconditioned before use or scrapped. He describes his experiences with the protection of small parts required for a mine railway. By storing them under boiled water covered with a layer of oil rusting was prevented; when the parts were required, the water was drawn off from the bottom of the containing vessels, so that as the level sank the parts became coated with the oil, which protected them until they were built into their places in the structure. This was found to answer better than coating with tar.

Protection of Underground Pipe from Corrosion. E. O. Slater. (Industrial and Engineering Chemistry, 1929, Vol. 21, Jan., pp. 19-21). The author deals with the use of protective coatings for pipes. The types of coatings available for underground pipes are enumerated; a method used in California is described. This consists of a paint, or a combination of a paint and a reinforcing cotton wrapper; or a paint, a wrapper, and a hot bitumen. One product successfully used consists of specially processed native bitumens from Trinidad and elsewhere. The priming coat made by the proper blending of the bitumens and dissolved in a suitable volatile thinner is applied by hand brushing, and put on immediately after sand-blasting the pipe. This coat is followed by another made of the same base materials but blended to a consistency of molasses. After drying for about one day a second coat is applied. Where greater thickness of the coating is desired the above treatment is followed by a spiral wrap of impregnated reinforcing cotton, and covered with one or two coats of the heavy coating. When more protection is needed a second wrapping and extra coats are applied.

Economies Feature Enamelling Plant. R. A. Fiske. (Iron Age, 1929, Vol. 123, Jan. 10, pp. 135-139). An illustrated account is given of the layout and equipment of the new enamelling plant recently constructed by the George D. Roper Corporation, Rockford, Illinois. The heat reclaimed from the enamel burning furnaces is used for the enamel driers. A tile heat reclaimer is built into each gas-heated burning furnace, and heated air is distributed by an overhead duct system.

Well-Designed Enamelling Plant. (Iron Age, 1929, Vol. 123, Apr. 11, pp. 1016-1018). The equipment of the new plant of the Toledo

Porcelain Enamel Products Co., Toledo, Ohio, for the enamelling of castings, is described and illustrated. The castings are enamelled in a series of spray booths arranged in a straight line.

How Enamel is Applied to Castings in Pennsylvania Plant. J. B. Nealey. (*Iron Trade Review*, 1929, Vol. 84, Mar. 14, pp. 707-708). An outline is given of the practice adopted at an American plant for the enamelling of castings.

Cast Iron Suitable for Enamelling. A. Müller. (*Giesserei Zeitung*, 1929, Vol. 26, Mar. 15, pp. 158-160). The author discusses the influence of the impurities in cast iron on its ability to be enamelled. He gives practical notes on charging the furnace and melting the metal, and indicates the composition of an iron that will enamel well.

On a New Method for Testing the Opacity of Protective Coatings Against Corrosion. J. Cournot. (*Revue de Métallurgie, Mémoires*, 1929, Vol. 26, Feb., pp. 76-77). The method is intended for testing the porosity of coatings on steel or copper. Filter paper is impregnated with ferrieyanide and alkali chlorides; it is very gently but rapidly moistened with water and laid on the surface to be tested. After about 3 min., prussian blue stains show where porosity has occurred. The paper may be washed in water to remove the excess of ferrieyanide; the stains remain. The process is useful for examining electro-deposits. In the case of deposits of chromium or nickel on copper-plated steel, if the perforation extends through only the top layer the stain is brown (due to copper ferrieyanide), but if the perforation penetrates both deposits the colour is blue, the brown of the copper compound being masked. The method is not so sharp with zinc and cadmium coatings, as the colour of their ferrieyanides (white and yellow respectively) tends to cloak the intensity of the colour of the iron or copper. Tin foil and aluminium foil intended for wrapping foodstuffs can be tested for porosity by laying a sheet on a thoroughly clean and polished steel plate and applying the test paper.

PHYSICAL AND CHEMICAL PROPERTIES.

PROPERTIES AND TESTS OF CAST IRON.

Design of Engineering Castings in Relation to Tests. J. G. Pearce. (Paper read before the Institute of British Foundrymen, Dec. 1, 1928 : Foundry Trade Journal, 1929, Vol. 40, Jan. 24, pp. 67-71). Within the grey range of cast iron there is a continuous increase in strength as the cast section diminishes, for tensile, compressive, torsion, and transverse tests. The nature of the curve of change depends upon composition and other factors. When the results obtained from the transverse test are properly interpreted by working out transverse rupture stresses, there is a relationship between tensile and transverse tests. For separately cast round bars the ratio may be taken as 1.8 to 2 for $\frac{\text{transverse}}{\text{tensile}}$ and as 4 for $\frac{\text{compression}}{\text{tensile}}$. Ratios between other tests should be used with caution until the tests are standardised. The change in strength with section can conveniently be followed by testing in transverse bars of different diameters from the same melt. If a series of size-strength curves are prepared for different mixtures, it becomes possible to chart the connection between strength and those elements of composition which usually vary as between different mixtures in the same foundry.

The Influence of Span on Transverse Rupture Stress. J. G. Pearce. (Bulletin of the British Cast Iron Research Association, 1929, No. 23, pp. 97-98). The transverse rupture stress of cast iron is affected not only by composition and diameter, but by span, and hence in order to obtain strictly comparative results between bars of one size and bars of another size of the same material, obviously the span should be constant. The main consideration for fixing the span in the transverse test is usually that of deflection, the span chosen being such as will yield a readable deflection of, say, not less than one-tenth of an inch. This is the case in B.E.S.A. specification 321, in which the specified deflections all lie between 0.10 in. and 0.15 in. To get this, the centres for the 0.875-in. bar were chosen as 12 in., whereas for the remaining two bars (1.2 and 2.2 in.) the distance between centres is 18 in. The considerations outlined by the author suggest the desirability of adopting 18 in. as standard and of bringing the small bar into line with the remaining two bars so that transverse rupture stresses obtained on the three sizes in the same iron would be affected by no other variable. In testing long bars it will be evident that the

weight of the bar forms a greater fraction of the breaking load than is the case with a short bar. The author, however, has not found the weight even of the heaviest bars an appreciable proportion of the difference shown above, which is to be attributed to the span and not to the additional weight or the slower rate of cooling of long as compared with short bars.

The Shear Test not a Satisfactory Test for Cast Iron. W. Jolley. (Foundry Trade Journal, 1929, Vol. 40, Apr. 4, pp. 247-248; Apr. 11, pp. 273-276). The author reports the results of a series of tests carried out to determine the reliability of the shear test for cast iron. He concludes that the tensile test, which is a test of the structure of the metal, has been considerably misrepresented. There is no doubt that satisfactory and uniform results can be obtained when the tests are carefully conducted. The present shear test methods do not appear to give uniform results; also the $\frac{\text{shear}}{\text{tensile}}$ results of different investigators vary considerably, which indicates the unreliability of this test, and to suggest this as a standard test for cast iron would result in utter confusion in so far as figures put forward from the shear test to represent the tensile test cannot be fully agreed upon. The method of obtaining the test-pieces gives a surface that would not be satisfactory for consulting engineers; also to calculate the results from a trepanned test-piece 0.005 in. out of round would not be advantageous to the metal, as the size would be taken at the largest diameter. Unless satisfactory testing apparatus and test-pieces—machined true to size—are used, it appears that it is impossible to avoid a bending strain during testing, which would give false results. No regular relation has been found to exist between shear and transverse tests, but apparently the transverse test is universally accepted as one of the standard tests for cast iron. The tensile test in conjunction with the transverse deflection and hardness tests appears to be the most satisfactory method of determining the quality and structure of cast iron used for the manufacture of general castings. A small test-piece, 0.22 in. in diam., as suggested for the shear test, is out of all proportion for representing the quality of the metal, &c., in castings. The paper is followed by a contribution to the study of shear testing by J. Shaw.

Investigation of the Relationship between the Resistance to Compression and the Bend Strength of Cast Iron. S. Nadasan. (Die Giesserei, 1928, Vol. 15, Dec. 14, pp. 1251-1253). The author has developed a formula connecting the compressive strength and the bend strength of high-manganese cast irons. By means of a frequency curve he shows its practical applicability. He has, further, shown that a manganese content up to over 6 per cent. has no influence on the strength of cast iron.

Fatigue Tests of Cast Iron. W. R. Needham. (Iron and Steel Industry, 1929, Vol. 2, Jan., pp. 101-102).

Properties of Cast Iron of Interest to the Metallurgist, Founder, and Engineer. (American Foundrymen's Association, Apr. 1929). A list has been prepared by a sub-committee of the Grey Iron Committee of the American Foundrymen's Association classifying the different properties of cast iron. The properties are grouped under three headings. The causative properties are considered to be chemical composition and physical constitution. Under formative properties are listed all those properties which influence the production of a sound casting, and which affect the condition of the metal in the finished state. In the third group are included those properties peculiarly of interest to the engineer.

Research Problems in the Grey Iron Foundry. J. W. Bolton. (Transactions of the American Foundrymen's Association, 1928, Vol. 36, pp. 469-512). Grey irons may be classified into 40 or more groups according to their silicon and carbon contents. The irons within these groups may be subdivided further according to their cooling rates. The difficulties of obtaining exact data on absolute cooling rates are pointed out. The ratio $\frac{\text{volume}}{\text{surface area}}$ is used to define relative cooling rate. Several examples are cited which show that it may be possible to determine some of the properties of castings by means of properly chosen test-bars, yet it is necessary that the limitations of the tests be understood and their interpretation be carefully made. A portion of the paper is devoted to a discussion of several test methods. The value and limitations of the tensile test are enumerated, and recent methods of conducting shear and uniformity tests are explained. The balance of the paper is given to a discussion of the properties of various groups of iron. The use of the sum *per cent. carbon* + 0.30 *per cent. silicon* is advocated for indicating the cumulative effect of these elements on some of the mechanical properties of bars.

Heat Treatment and Properties of Cast Iron. P. Schoenmaker. (Blast-Furnace and Steel Plant, 1929, Vol. 17, Feb., pp. 283-286; Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 170-173). The author describes the effects of the control of the initial melting temperature and of subsequent heat treatment upon the properties and structure of cast iron.

The Use of Cast Iron for Structural and Other Purposes. O. Bauer. (Mitteilungen der deutschen Materialprüfungsanstalten, 1929, Sonderheft V., pp. 1-11).

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Cast Iron for Automobile Engines. H. C. Jay. (Foundry Trade Journal, 1929, Vol. 40, Mar. 14, p. 204). A brief discussion of the composition and properties of cast iron used for the production of automobile engines. A table is included showing the composition of suitable irons as proposed by various authorities.

Metallurgical Specifications for High-Class Cast Irons. H. J. Young. (Metallurgist, 1929, Feb., pp. 28-29). The author discusses the variability of cast iron, and points out various fallacies which enter frequently into cast-iron specifications; he suggests points to which attention should be directed in order to tighten up the control and ensure that reliable material suitable for the intended purpose is supplied.

Eutectic Cast Iron. A. Mitinski. (Paper read before the Paris Foundry Congress, 1928: Iron and Steel of Canada, 1929, Vol. 12, Feb., pp. 55-56).

The Present Status of Knowledge of the Machinability of Cast Iron. A. Wallich and K. Krekeler. (Die Giesserei, 1928, Vol. 15, Dec. 28, pp. 1289-1292).

The Theory of Cast Iron. (Giesserei Zeitung, 1929, Vol. 26, Mar. 1, pp. 137-140). This article, in German, is based on one by A. B. Everest. (See Journ. I. and S.I., 1928, No. II. p. 384.)

The Chemical Composition an Insufficient Measure of Quality. E. Piwowarsky. (Die Giesserei, 1929, Vol. 16, Apr. 5, pp. 318-321). The reasons for the different properties of cast irons of similar chemical composition are explained by the work of previous investigators in the light of modern knowledge.

Influence of Carbon and Silicon Variations in Grey Cast Iron. D. G. Anderson and G. R. Bessmer. (Transactions of the American Foundrymen's Association, 1928, Vol. 36, pp. 453-460). The authors present the results of experiments made to determine the effect of varying the carbon content in grey iron while keeping the silicon content constant. It is shown that the total carbon content of grey iron of the 2 per cent. or higher silicon type may be somewhat reduced without materially increasing the amount of combined carbon in the casting. This reduction of carbon results in some improvement in the physical properties.

The Mechanical Properties of Deoxidised Cast Iron. P. Bardenheuer and K. L. Zeyen. (Die Giesserei, 1928, Vol. 15, Nov. 9, pp. 1124-1128). The opinions of various investigators on the effect of oxygen on the mechanical properties of cast iron are reviewed. Experiments

are recorded, showing that deoxidation of cast iron by ferro-titanium raises the graphite content somewhat and, consequently, lowers the strength properties. Only in annealed chilled castings did titanium increase the elongation. The influence of sulphur on deoxidised cast iron is not so marked as on ordinary cast iron; up to 0.27 per cent. its ill effects are hardly noticeable. A phosphorus content up to 0.3 per cent. has a favourable effect on deoxidised cast iron.

The Influence of Copper on Cast Iron. C. Pfannenschmidt. (*Die Giesserei*, 1929, Vol. 16, Feb. 22, pp. 179-182). After a review of the literature on the subject, the author describes his own tests made on cast iron containing copper to determine the effect of that element on the physical properties and on the resistance to very dilute acids. The bend strength, tensile strength, and Brinell hardness increased with the addition of copper, as did also to a slight extent the amount of graphite. The addition of copper reduced the solubility of the irons in the dilute acids.

The Influence of Nickel-Chromium on Cast Iron. A. B. Everest and D. Hanson. (*Foundry Trade Journal*, 1929, Vol. 40, Jan. 3, pp. 5-10). This paper forms the final report of the work carried out at Birmingham University. Tests were carried out in the laboratory and on a practical scale to determine the influence of nickel and chromium on a high-grade cylinder iron. Cast iron may in general be toughened and hardened either by reducing its silicon content or by the addition of a suitable hardening element such as chromium, but in both cases an increase in the depth of chill shown by the iron at once becomes apparent, and would render any casting made from this iron unmachinable, due to hard carbide spots in its structure. Nickel eliminates this chill tendency without softening the parts of the casting which are already grey. It has been found that with nickel additions the grey parts are actually hardened while the thin sections are being changed from white to grey. A low-silicon iron possesses a fine grain, associated with good strength properties. An alternative method of improving the iron has been investigated. To obtain the best effects of nickel in cast iron a reduction in the normal silicon content is desirable in order to counterbalance the graphitising action of the former element. This reduction in silicon is not always a practical proposition; consequently, to counterbalance the softening effect of the nickel, the alternative method of adding chromium was investigated. The results indicate a slight preference for the nickel-chromium iron as compared with the low-silicon iron when mechanical test results are considered. Chromium and nickel additions must be suitably balanced if good results are to be obtained at will, and it is necessary to determine the ratio in which they should be added. The most rational way to make comparisons is to fix the chromium-nickel ratio necessary to maintain a constant chilling tendency, since this ensures approximately constant

machinability. The balanced ratio is not a constant quantity, but one that varies somewhat, not only with the base iron and foundry practice, but more particularly with the amount of chromium added.

Alloy Cast Irons. A. B. Everest. (Paper read before the Institute of British Foundrymen : Foundry Trade Journal, 1929, Vol. 40, Jan. 17, pp. 45-48). The general principles governing the choice of an alloying element for cast iron are discussed, and the influence of nickel, chromium, and aluminium is dealt with.

Effects of Nickel and Chromium on Cast Iron. D. Hanson. (Metallurgist, 1929, Mar., pp. 38-40 ; Apr., pp. 56-60). The effects of alloy additions to cast iron are briefly discussed, followed by considerations of the following subjects : Effect of nickel in cast iron ; comparison of the effects of nickel with those of silicon ; the effects of nickel and silicon when present together ; the effect of chromium ; comparison of the effects of nickel, silicon, and chromium ; practical applications.

The Influence of Nickel on Combined Carbon in Grey Iron. J. R. Houston. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Jan., pp. 145-157, 169). Photomicrographs are given showing the influence of nickel on the combined carbon in cast iron.

The Growth of Grey Cast Iron, with Reference to the Elements Nickel and Chromium. E. Piwowarsky and W. Freytag. (Die Giesserei, 1928, Vol. 15, Nov. 30, pp. 1193-1200). It was established experimentally that nickel, contrary to usually accepted ideas, does not increase the growth of cast iron. Up to 3 per cent., the effect of that element on the graphite form in strongly overheated high-quality cast irons was not noticeable ; only at higher contents (5 to 6 per cent.) was a coarsening of the graphite recognisable. Jolting was not found to effect any diminution of growth. Strongly overheating the molten metal (graphite refinement) reduced the tendency towards growth ; vacuum-melting (greater density and reduced gas content) decreased the growth very much. The volume constancy of cast iron containing graphite in the form of temper carbon was found to be greater than that of a similar iron containing fine eutectic graphite. Tests made with superheated steam (the apparatus is described) showed that the volume changes in that medium at 450° C. were very small, but that at 550° C. a considerable growth occurred. The effect of the melting treatment (graphite refinement) was also observable in these tests.

The Influence of Nickel and Chromium upon the Growth of Grey Cast Iron. (Foundry Trade Journal, 1929, Vol. 40, Feb. 28, p. 156).

An abridged translation of the above paper by E. Piwowarsky and W. Freytag.

The Growth of Cast Iron. E. Piwowarsky and H. Esser. (*Die Giesserei*, 1928, Vol. 15, Dec. 21, pp. 1265-1270). A review of the work of previous investigators. A bibliography of 41 references is given.

The Growth of Cast Iron. F. Wüst and O. Leihener. (*Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1928, Vol. 10, pp. 265-281). The influence of the chemical composition on the growth of cast iron is masked by other factors. It is shown that the growth in a neutral atmosphere cannot be explained by the decomposition of the cementite alone. The finer the form of the graphite, the smaller is the amount of the growth. The material in the middle of a casting grows more than does the exterior metal. It is shown that the gas content of the cast iron has an important bearing on the growth.

Constituents and Texture of Cast Irons. J. Seigle. (*Revue de l'Industrie Minérale*, 1928, Nov. 1, pp. 427-442). The constituents entering into the composition of cast iron, their influence on the texture and mechanical properties, and perlit cast iron are discussed.

Theories on Graphitisation. H. A. Schwartz. (Paper read before the Association Technique de Fonderie de France, Oct. 1928: *Foundry*, 1928, Vol. 56, Nov. 1, pp. 871-873; Nov. 15, pp. 918-920). The author reviews existing theories on the formation of graphite in cast iron.

The Spatial Form of Graphite. F. Roll. (*Die Giesserei*, 1928, Vol. 15, Dec. 21, pp. 1270-1274). The various forms of graphite encountered in cast iron are discussed. The author builds up models of the particles of graphite by repeatedly removing very thin slices from the surface of the specimen, taking a photograph (or making a sketch) of the particles through a microscope after each slice is removed.

The Thermal Conductivities of Grey Cast Irons. J. W. Donaldson. (*Proceedings of the Institution of Mechanical Engineers*, 1928, No. 11., pp. 953-983). The thermal conductivity of grey cast iron varies from 0.110 to 0.137 calories per cm.-sec., and decreases as the temperature increases. The values obtained for thermal conductivity depend not only on composition but also, although to a much smaller extent, on structure. The influence of silicon is to lower the conductivity considerably. Nickel has a similar effect, as have also manganese and vanadium, although to a lesser degree. Chromium and tungsten tend to raise the thermal conductivity. As regards structure, free ferrite appears to be a much better conductor of heat than eutectoid pearlite. Heat treatment at 550° C. at first increases the thermal conductivity,

due to the pearlite decomposing to form ferrite and graphite, after which the oxidation of iron in the vicinity of the graphite flakes causes a slight decrease.

The Thermal Conductivity of Grey Cast Iron. G. Graf. (Giesserei Zeitung, 1929, Vol. 26, Jan. 15, pp. 45-46). The following matters are dealt with: The various forms of heat transference; thermal conductivities of metals; experimental determination of the thermal conductivity of cast iron; influence of accompanying elements and hardness; relation between thermal conductivity and specific gravity; influence of temperature; radiation value of cast iron.

Influence of Repeated Heatings and Coolings on the Structure of Grey Cast Iron. V. N. Svechnikov. (Journal of the Russian Metallurgical Society, 1928, No. 3, pp. 93-104). (In Russian.)

PROPERTIES AND TESTS OF IRON AND STEEL.

Armco Pure Ingot Iron. E. L. Dupuy. (Revue de Métallurgie, Mémoires, 1928, Vol. 25, Nov., pp. 637-647). The manufacture, properties, and uses of Armco iron are reviewed.

The Application of Science to the Steel Industry. W. H. Hatfield. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Mar., pp. 474-502; Apr., pp. 652-669; May, pp. 817-836; June, pp. 986-1026). The Edward De Mille Campbell Memorial Lecture presented on Oct. 10, 1928. Section I. of the lecture is of an introductory character, in which the author alludes to the part played by E. D. Campbell in the development of iron and steel metallurgy, and indicates a number of metallurgical problems requiring solution. In Section II. British practice in steel manufacture is described. The various methods of oxygen determination are reviewed and the defects of each are pointed out. Temperature measurements of liquid steel are also discussed and the precautions necessary for accurate results are pointed out. The chief portion of this section is devoted to the production of sound steel, the information given being based on the Reports of the Committee on Heterogeneity of Steel Ingots of the Iron and Steel Institute. Manipulation and treatment is discussed in Section III., the subject being dealt with under the following headings: heating for hot-work; normalising and annealing; hardening and tempering; effects of forging on structure and properties; influence of composition and temperature on thermal conductivity of steels; specific heat of steels as affected by temperature and composition; specific heat of pure iron and effect of composition on specific heat. In Section IV. the properties

of special steels are dealt with, Section V. deals with acid and corrosion resistant steels, Section VI. with the influence of temperature on the properties of steels, and Section VII. with tool steels and cutlery.

Physical Properties of Ferrous Metals. (Research Group News, Jan., 1929; Heat Treating and Forging, 1929, Vol. 15, Mar., pp. 307-310; Apr., pp. 442-445). The meaning of the various physical properties, and tests for their measurements, are explained.

Apparatus for Measuring Changes of Cross-Section of Loaded Bars. H. Sieglerschmidt. (Messtechnik, 1929, Vol. 5, Jan., pp. 8-13). The apparatus works on the principle of the optical lever. The results of measurements made on steel rods are recorded.

The Deformation of Metals, with Special Reference to the Tensile Test. C. H. Desch. (Paper read before the Institution of Engineers and Shipbuilders in Scotland, Feb. 26, 1929; Iron and Coal Trades Review, 1929, Vol. 118, Mar. 8, p. 361; Mar. 15, p. 391). Plastic deformation, information yielded by the tensile test, limit of proportionality, true elastic limit, determination of yield point, true stress, significance of reduction of area, steel hardening in tension, failure by shear, reduction as an indication of ductility, the compression test, plastic deformation at high temperatures, cold-work, viscous flow, and application of load are discussed.

Tensile Tests of Rods and Wire of the Same Iron. J. Muir. (Journal of the Royal Technical College, Glasgow, 1929, Vol. 2, Part I., Jan., pp. 5-11). The elastic properties of rods and wires of the same iron are compared; and attention is drawn to a large increase observed in yield-point extension without any corresponding change in the yield-point stress.

Studies of the Tensile Test on Crystalline Materials. E. Schiebold and G. Richter. (Mitteilungen der deutschen Materialprüfungsanstalten, 1929, Sonderheft V., pp. 68-96).

Proposed New Criteria of Ductility from a New Law Connecting the Percentage Elongation with Size of Test-Piece. D. A. Oliver. (Proceedings of the Institution of Mechanical Engineers, 1928, No. II., pp. 827-864). The results are given of an investigation carried out to determine the law of variation of percentage elongation with size of test-piece.

The Stress-Strain Diagrams of a Heat-Treated Nickel-Chrome Steel. A. Robertson and A. J. Newport. (Metallurgist, 1929, Feb., pp. 23-26; Mar., pp. 35-36). The results of the determination of the stress-strain relationships in compression and in tension in heat-treated

nickel-chrome steel tubes are recorded. The composition of the tubes used for compression tests was carbon 0.25, nickel 4.1, and chromium 1.25 per cent., that of the tension test-pieces was approximately the same. An optical extensometer was used for the compression tests.

The Fracture of Notched Tensile Test-Pieces. (Metallurgist, 1928, Vol. 4, Dec. 28, pp. 179-180). An abstract, with comments, of an article by W. Kuntze (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Aug., pp. 109-117 : see Journ. I. and S. I., 1928, No. II. p. 393).

Concerning the Yield Point in Tension. J. M. Lessells. (Proceedings of the American Society for Testing Materials, 1928, Vol. 28, Part II., pp. 387-397). The author criticises the methods used in the determination of certain tension test values, which methods have been suggested by the American Society for Testing Materials for standardisation. The paper shows that the "Johnson limit" may, in certain cases, be far removed from the proportional limit and suggests certain improvements in the yield-point determination.

The Physical Significance of the Yield Point. (Metallurgist, 1928, Vol. 4, Dec. 28, pp. 186-187). Two articles, one by W. Kuntze and G. Sachs (Zeitschrift des Vereines deutscher Ingenieure, 1928, Vol. 72, July 21, pp. 1011-1016 : see Journ. I. and S. I., 1928, No. II. p. 391), the other by Kühnel, Mohrmann, and Karth (Ibid., 1928, Vol. 72, Sept. 1, pp. 1226-1232 : see Journ. I. and S. I., 1928, No. II. p. 392), are abstracted and commented upon.

Resistance to "Long-Time" Test Stresses and other Properties of Rail Steel. R. Mailänder. (Stahl und Eisen, 1928, Vol. 48, Oct. 18, pp. 1477-1479). The melting and refining operations in the manufacture of basic rail steel at the works of the Algoma Steel Company and Carnegie Steel Company are described, analyses of the product are given, and particulars of the type and dimensions of the ingot moulds used are stated. These were of the Gathmann type and the ordinary type. Tests were carried out on the finished rails, specimens being subjected to tensile, impact, and hardness tests, and particularly to an extensive series of endurance tests. The rails from the material cast in the Gathmann moulds showed some superiority over those from the ingots cast in the ordinary moulds. The heats cast in the Gathmann moulds were of killed steel, and unkilld in the ordinary mould.

Hardness Measurements on the Flow Figures of Tensile Test-Pieces. M. Moser. (Stahl und Eisen, 1928, Vol. 48, Nov. 15, pp. 1601-1606). In the elongated part of a steel tensile test-piece the steel does not flow uniformly but in zones. Each zone stretches at first till a certain degree of hardness is attained, and then remains nearly stationary

with the hardness unaltered while another zone elongates. Only when all the zones throughout the length of the test-pieces have been elongated does a further uniform increase in hardness set in over the whole elongated part. The experiments to determine the changes in hardness in the ranges of elongation were made on a steel containing 0.08 per cent. carbon and 0.01 per cent. silicon.

Further Studies of the Yield Point. (Metallurgist, 1928, Vol. 4, Dec. 28, pp. 191-192). An English abstract of the above paper by Moser.

The Long-Time Tensile Test. (Génie Civil, 1929, Vol. 94, Feb. 16, pp. 167-169). The long-time testing apparatus used in the laboratories of Messrs. Brown, Boverie & Co. is described, and some test results are recorded.

The "Creep" Strength of a High-Nickel High-Chromium Steel, between 600° and 800° C. H. J. Tapsell and J. Remfry. (Department of Scientific and Industrial Research, 1929, Engineering Research, Special Report No. 15, London: H.M. Stationery Office). The material used in this investigation had the following composition: Carbon 0.46, silicon 1.20, manganese 1.09, nickel 26.5, chromium 14.0, tungsten 3.59, sulphur 0.028, and phosphorus 0.026 per cent. Short-time tensile tests were carried out on the material as received, at air temperature, 500°, 600°, 700°, and 800° C. Each specimen was soaked at the required temperature for at least half an hour before applying the load, and about 3 to 4 min. were occupied in carrying out the test. The results show that the ultimate tensile stress decreased from 45.9 tons per sq. in. at 15° C. to 17.2 tons per sq. in. at 800° C. Tests at 600°, 700°, and 800° C. were made under prolonged tensile stresses. The method of test consisted in applying various loads, giving decreasing values of initial stress and determining for each stress the time taken for failure to occur, unless the time involved was too prolonged. Readings of strain ("creep" in inches per in. of gauge length) were taken at frequent intervals, and curves connecting strain and duration of test for all the tests were obtained, and are shown graphically for the upper and lower temperature limits. The relations between stress and time to fracture at different temperatures are also shown, from which the limiting "creep" stresses, or stresses giving very long life, have been deduced. Complete results obtained for the "creep" tests are tabulated. The elongations on broken test-pieces for any particular temperature varied somewhat. A microscopical examination of some of the broken test-pieces showed that intercrystalline cracks developed under test at 800° C., and slightly at 700° C., but no cracks could be detected on one of the test-pieces tested at 600° C. The tendency to fail by intercrystalline cracking probably accounts for variations in final elongations.

The Calibration of Pendulum Impact Testers. M. Rudeloff. (*Mess-technik*, 1929, Vol. 5, Feb., pp. 31-38). The author's design of a pendulum impact tester is illustrated and described, and its calibration is explained.

On the Relation between Stress and Strain in the Impact Test. R. Yamada. (*Science Reports of the Tôhoku Imperial University*, Sendai, 1928, Vol. 17, pp. 1179-1211). The stress-strain curves were obtained with a Charpy impact machine by Körber and Storps' method, and the results were compared with those of the static test. The materials tested were carbon steels containing 0.1, 0.3, and 0.5 per cent. of carbon and nickel-chromium steels. At ordinary temperatures the maximum force was generally greater in the impact test than in the static one. The maximum force generally increased with the velocity of deformation. The absorbed energy generally increased with the velocity of deformation, and it was also affected by the shape and the depth of the notch. When the breadth of the test-piece was altered, other dimensions remaining the same, the maximum force increased a little more rapidly than would be proportional to the breadth. The absorbed energy increased rapidly, not being generally proportional to the breadth. When the ratio of the thickness to the breadth was comparatively small, this proportion nearly held good. Thus the results obtained by M. Moser are shown to be a special case. When the cross-sections of the test-pieces were all similar and the shape and the depths of the notch remained the same, the maximum force and the absorbed energy varied in proportion to the product of the breadth and the square of the thickness of the test-piece at the notch. The brittleness in steels at low temperatures was also investigated. In general, the temperature at which steels become brittle was higher in the impact than in the static test. In the impact test, both the maximum force and the absorbed energy decreased similarly in the brittle range.

The Effect of the Velocity of Test on Notch Brittleness. J. G. Docherty. (Paper read before Section G of the British Association, Glasgow, Sept. 11, 1928: *Engineering*, 1928, Vol. 126, Nov. 9, pp. 597-600). The author first summarises previous work and shows the considerable difference of opinion which exists concerning the relation between slow bend and impact tests, especially for steels. He next describes his machine, constructed to determine whether the differences between slow bend and impact tests were due, in some degree, to the impactive nature of the latter, or whether they were due merely to the increased rate of bending. The machine was designed to use standard 10-mm. by 10-mm. Izod notched specimens. The test-piece was held in a vice in the usual way; a striker was pushed downwards by a hydraulic ram (or other means) at a predetermined rate, the slide carrying the striker being fitted with guides and ball-

bearings so as to withstand the strains imposed by the bending of the specimen without appreciable friction. Autographic records of the experiments were taken; the load applied was measured on a pressure gauge connected to a cylinder and plunger placed between the slider and the ram or other means employed to operate the testing machine. The results of tests on mild steel, nickel steel, and naval brass are recorded and discussed. The relation of the Izod results to the slow bend results is complex. With mild steel the Izod value lies well above any smooth curve that can be drawn through the slow-speed results; with nickel steel the Izod values lie distinctly low, while with naval brass the Izod value falls very near the slow-speed curve. The cold-work in mild steel "as rolled" has no appreciable effect on the bending tests. Photographs of specimens at various stages of bending are shown, and the various features in the autographic curves and in the manner of breaking of the test-pieces are discussed.

Repeated-Blow Impact Tests. R. H. Greaves. (Metallurgist, 1929, May, pp. 67-68). A brief review of various investigators' work on the repeated-blow impact test.

Valuation of Materials by Notched-Bar Tests. W. Schwinning. (Zeitschrift des Vereines deutscher Ingenieure, 1929, Vol. 73, Mar. 9, pp. 321-329; *abstract*, Metallurgist, 1929, May, pp. 79-80). The author deals with the following subjects: Notch-action during elastic and plastic deformation; influence of the type of fracture; the process of fracture in relation to temperature and speed of deformation; influence of the variation of notch-action on the process of fracture; and the question of the standardisation of notched-bar test-pieces.

The Notched-Bar Impact Test and Its Development: A Criticism. F. Fettweis. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Apr., pp. 625-674). In this lengthy report the author gives a historical account of the development of the notched-bar test, and then proceeds to describe the methods and apparatus for carrying it out, and discusses the questions of deformation, the manner in which rupture is produced, the character of the fracture, the law of similarity, the effects of temperature, speed of impact, form of test-piece; the dependence of the notch-toughness on the structure, heat treatment and chemical composition; the effect on the results of cold-working, ageing, and temper-brittleness; and the relation of notch-toughness to other properties. In conclusion, criticism is directed to the shortcomings of the test as a suitable one for judging the qualities of a material, on account of its dependence on so many variables. The article concludes with an excellent bibliography of the whole subject of notched-bar impact testing covering the period from 1885 to date and containing 700 references to literature.

Notch Action in Science and Practice. E. Seidl. (Mitteilungen der deutschen Materialprüfungsanstalten, 1929, Sonderheft V., pp. 122-130).

Notch-Toughness and Static Data. W. Kuntze. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Mar., pp. 583-590). The degree of notch-toughness is derived from the joint effect of the resistance to deformation and breaking strength. The resistance to deformation increases under dynamic stress and is dependent on the speed of impact to which the material is subjected. For the measurement of this property no formula has yet been devised. The breaking strength varies with the degree of deformation. Graphically the point at which the breaking strength curve and the curve of true stresses cut one another gives the point at which fracture takes place, and the work of impact producing fracture may be calculated from the work diagram. From the peculiar form of the breaking strength curve, it can be judged that only the slightest change in the specific speed of load application is sufficient to produce a quick (brittle) fracture, or a long-drawn-out (tough) fracture.

Influence of the Rolling and Annealing Temperature on the Strength Properties and Structure of Cold-Rolled Low-Carbon Steel. A. Pomp and S. Weichert. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 301-316). Band steel, 28×2 mm., with 0.08 per cent. of carbon, was rolled at room temperatures and at temperatures of from -70° to $+500^{\circ}$ C., with varying amounts of draft. The specimens rolled at room temperature were also annealed for 3 hr. between 100° and 900° C. With increasing degree of rolling, the tensile strength and hardness increased, while the extension and Erichsen value fell. Raising the rolling temperature had similar effects, while lowering it below room temperature produced opposite results. On annealing the specimens rolled at room temperature, distinct recrystallisation was first noticeable at 600° C., while the strength properties began to change at much lower temperatures.

The Influence of the Reduction of the Draft and of the Annealing Temperature on the Mechanical Properties and Structure of Cold-Rolled Thin Sheets. A. Pomp and L. Walther. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1929, Vol. 11, pp. 31-35). Thin sheets of various gauges were cold-rolled to different thicknesses and were then annealed. Annealing for 3 hr. at 920° C. gave the best mechanical properties and a uniform structure, irrespective of the degree of deformation. Annealing at 750° C. for 3 hr. gave nearly the same results, provided that deterioration in the critical range was minimised by a cold deformation exceeding 20 per cent. Annealing for 3 hr. at 650° C. was insufficient to remove the cold-work. Tests

on other sheets of various gauges reduced about 30 per cent. by cold-rolling and annealed at 750°C . showed that the gauge was without effect on the deep-drawing properties of the annealed sheet.

Recrystallisation during Hot-Rolling. W. Tafel, H. Hanemann, and A. Schneider. (Stahl und Eisen, 1929, Vol. 49, Jan. 3, pp. 7-12). After referring to the work of previous investigators on the question of the recrystallisation during deformation of steel in the hot state, experiments are described which were made with the object of determining whether the grain-size following a given amount of hot deformation was dependent on the original grain-size. Steel bars were rolled at 1000°C . under a pressure producing a 7 per cent. reduction in the depth of the bar. The original grain-size of the different bars were: $1480\ \mu^2$, $3860\ \mu^2$, $7340\ \mu^2$, and $47,800\ \mu^2$. After rolling, the grain-size in all the bars was found to be about $800\ \mu^2$. Other similar bars were then rolled at 1000° , under a pressure producing a 14 per cent. reduction in the depth of the bar. The original grain-sizes were: $655\ \mu^2$, $950\ \mu^2$, and $1068\ \mu^2$, and after rolling, the grain-size of these bars was found in all cases to be $850\ \mu^2$. The conclusion of chief importance is that it is the pressure and temperature of the final pass that determines the final grain-size, and that this is not affected by the rolling conditions in the earlier passes. Further experiments showed that the longitudinal and transverse axes of the recrystallised grains were equal so long as the final pass was made at over 900° . Below that temperature the grains were elongated in the direction of rolling. A number of space diagrams are given which show clearly the effect on the final grain-size of very mild steel (0.03 per cent. carbon) rolled at temperatures ranging from 750° to 1200° , and at pressures giving a reduction of 4 to 40 per cent. in the depth of the bar.

The Strength Properties and the Angle of Fracture of Cold-Rolled Metals. F. Körber and H. Hoff. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 175-187). The mechanical properties of some non-ferrous metals and of electrolytic iron after various degrees of cold-rolling and in different directions in relation to the direction of rolling were investigated; the fractures of the flat test-pieces, and the directions in which they occurred in relation to the direction of rolling were studied.

The Theory of the Formation of the Angle of Fracture. F. Körber and E. Siebel. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 189-192). A theory of the mechanism of deformation during plastic deformation is propounded, according to which the deformation proceeds along two equal slip systems inclined to each other at an angle dependent on the situation of the mean principal stress. The theory satisfactorily explains the occurrence of the angle of fracture in flat (strip) test-pieces.

The Mechanical Properties of Single Metal Crystals and Crystal Aggregates. H. C. H. Carpenter. (Proceedings of the South Wales Institute of Engineers, 1929, Vol. 44, pp. 541-605). The author describes fundamental phenomena and illustrates various aspects of the subject to show the relations between the crystal structure of metals and their mechanical properties.

The Mechanical Properties of Materials as shown by Studies on Single Crystals. W. P. Davey. (Paper read before the American Society of Mechanical Engineers, Dec. 3 to 7, 1928: Mechanical Engineering, 1929, Vol. 51, Apr., pp. 280-282). The elastic after-effect, the elastic limit, the mechanism of plastic deformation, and the strength of materials, are explained on the basis of A. Joffé's experimental work.

On the Mechanism of Technical Deformation Processes. K. Hübers. (Röhrenindustrie, 1928, Vol. 21, Nov. 8, pp. 453-455; Nov. 22, pp. 473-475). The internal changes which occur in metals during deformation processes (rolling, compressing, drawing, &c.) are discussed.

Cold- and Hot-Working of Metals. W. Rosenhain. (Metallurgist, 1928, Vol. 4, Nov. 30, pp. 168-169). The conclusion of a previous article (*see* Journ. I. and S.I., 1928, No. II. p. 404). In the present instalment the absence of work-hardening at high temperatures, and the occurrence of creep within a temperature range in which work-hardening and recrystallisation may take place if the time factor be sufficient, are discussed.

Some X-Ray Studies of Cold-Worked Steel. F. C. Elder. (Paper read before the American Iron and Steel Institute, May 1929). The author shows the changes that take place in the pinhole type of X-ray patterns during the cold-drawing of low-carbon steel. Photographs show wire after various degrees of cold-work. Judging from the evidence secured, cold-work takes place in two stages. In the first stage, in stretching or cold-drawing through a die, the crystals are apparently fragmented. This stage extends up to an amount of cold-work equivalent to 10 to 20 per cent. reduction in area. The extent of this stage depends chiefly on the grain-size, that is, the smaller the grain the sooner the appearance of the preferred orientation, which is characteristic of the second stage. The persistency of the cold-worked structure, even after annealing at fairly high temperatures wires which had previously been cold-drawn 80 per cent., is shown, although in less severely cold-worked wires evidence of the cold-work is removed by comparatively low-temperature annealing.

The Change of Specific Volume of Steel by Cold-Working. M. Oknoff. (Journal of the Russian Metallurgical Society, 1928, No. 1, pp. 11-13). (In Russian.)

New Investigations Concerning the Theory of the Hardening of Steel. E. Scheel. (*Archiv für das Eisenhüttenwesen*, 1928, Vol. 2, Dec., pp. 375-388). A consideration of the conditions necessary to produce hardness in steel. The more rapid the cooling by quenching, the more complete is the transformation of austenite into martensite. This behaviour is accounted for by the fact that the existence of stresses is essential for bringing about the transformation. In quenching it is heat stresses which come into play. In slow cooling to below 0° , the stresses are due to the different heat expansions of austenite and martensite. In tempering three stages are observed. The first and third stage represent transformations of the martensite, and the second a transformation of the austenite. At the third stage there is also the possibility of a carbide transformation. Various factors which influence the hardness of quenched steel are discussed, and it is shown that refinement of the grain is responsible for a considerable increase in the hardness. It is expected that more light will be thrown on the causes of the hardening of steel, when the explanation of the spreading of the X-ray lines of martensite has been found.

The Nature of Hardness and the Hardness of Metals. (Iron and Coal Trades Review, 1929, Vol. 118, Mar. 29, pp. 472-473). At a joint meeting of the Yorkshire Section of the Society of Chemical Industry and the local branch of the Institution of Mechanical Engineers, held at Leeds on Mar. 12, 1929, a discussion took place on hardness, in which the nature of hardness was dealt with by C. H. Desch and the hardness of metals by H. O'Neill.

Relation between Various Degrees of Hardness of Unhardened Carbon Steel. A. Wallich and H. Schallbroch. (*Maschinenbau*, 1929, Vol. 8, Feb. 7, pp. 69-74). Steel containing from 0.1 to 1.0 per cent. of carbon was exposed to various hardening tests, and a curve was plotted showing the ratio of Brinell hardness to the new hardness coefficient, and corresponding equations are derived.

Hardness Testing in Mass Production. Schandt. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Apr. 6, p. 471). A brief description with a line drawing of a hardness tester designed by G. Gerber. The piece to be tested is placed on a table, and is raised by a screw till it meets the indenter, which it also raises until a gauge reads zero. The steady movement of a lever permits the indenting load to press upon the indenter; the load is removed, and the depth of indentation, due to the imposition of the main load, is read off on the gauge, which may be marked to show the hardness directly.

Relation of Nitrogen to Blue Heat Phenomena in Iron, and Dispersion Hardening in the System Iron-Nitrogen. R. S. Dean, R. O. Day, and J. L. Gregg. (*American Institute of Mining and Metallurgical*

Engineers, 1929, Technical Publication No. 193). In a study of hardening by reheating after cold-work, three kinds of iron were used—vacuum-melted electrolytic iron, electrolytic iron melted in air, and Armco iron. These materials in the form of forged bars, annealed at 980°C ., in vacuum, were reduced 30 per cent. in thickness by cold-rolling and then reheated to temperatures varying from 100° to 500°C . The vacuum-melted iron showed no hardening, while the air-melted iron increased markedly in hardness by reheating to 250°C . The Armco iron was intermediate. By melting in air, the electrolytic iron had taken up a very considerable amount of impurity, apparently nitride. Hardening took place on reheating air-melted iron which had been annealed but not cold-worked when a temperature of 350°C . was reached; whereas, in cold-worked material, hardening was pronounced at 250°C . It was concluded that commercial irons owe their property of hardening by reheating after cold-work, as well as their increase of tensile strength in the range 100° to 300°C . to the solution of small amounts of iron-nitride present. An examination of the iron-nitrogen system indicates that it is a typical dispersion hardening system which shows room-temperature hardening in a marked degree.

Wear Testing of Various Types of Steels. J. M. Blake. (Proceedings of the American Society for Testing Materials, 1928, Vol. 28, Part II., pp. 341–355). The paper describes apparatus developed to test the resistance of metals to abrasion under so-called “wet grinding” conditions. In principle, the machine is a very accurately controlled grinding machine in which all conditions as to abrasive, pressure, speed, time, and moisture or other liquid present are under the control of the operator. It is possible to approximate any given set of field requirements. The wear is measured by the amount of metal worn off in approximately 15,000 ft. of travel at a speed of 125 ft. per min., using a pressure of 50 lb. per sq. in. on a testing face of approximately 3 sq. in., and is expressed as the ratio of wear loss as compared with a standard (commercially pure iron) taken as 100. By varying the abrasive used, it has been possible to develop alloys specifically adapted to particular field requirements.

Frictional Wear Tests on Steels and their Application to the Study of Railway Rails. G. Ranque. (Revue de l'Industrie Minérale, 1929, Apr. 15, pp. 284–294). Wear resistance of steel can be determined only by direct methods. The Amsler machine, in which the wearing properties of the material in the form of discs or rollers is determined, is described. The variation of the weight of the rollers is a criterion of the wearing properties, but change in diameter is not. Certain precautions must, however, be taken, and they are enumerated. The process by which loss of metal occurs during “rolling,” with and without friction, is explained. As an example of the application of the test, the results of tests on rails are given.

Effect of Condition of Track on Wear of Rails. L. Lubimoff. (*Organ für die Fortschritte des Eisenbahnwesens*, 1928, Vol. 83, Oct. 15, pp. 438-442). The author presents a report on a series of observations made on three main railways in Russia. The effect of condition of ballast, ties, slope of rail, and the composition of the rail steel, are discussed.

The Drill Test as an Indication of the Machinability of Metals. G. Schlesinger and S. Patkay. (*Werkstattstechnik*, 1928, Vol. 22, Dec. 15, pp. 677-683).

Grain-Size Controls Toughness. T. W. Hardy. (*Iron Age*, 1928, Vol. 122, Dec. 20, pp. 1557-1562). It is pointed out that many of the important physical characteristics of steel, including machinability, capacity for hardening and mechanical properties, are definitely affected by grain-size in the McQuaid-Ehn test. The carburising test provides a simple and positive method of distinguishing between heats of steel with the same chemical analysis, yet responding differently in mass production.

Ageing of Boiler Material and its Prevention. F. Nehl. (*Zeitschrift des Bayerischen Revisions Vereins*, 1928, Dec. 15, pp. 315-317; Dec. 31, pp. 324-325; *Stahl und Eisen*, 1929, Vol. 49, Apr. 4, pp. 472-474). The occurrence of ageing in boilers, especially in those parts which may have to work at temperatures approaching blue heat, is highly dangerous, and is only to be prevented by the avoidance of any kind of cold deformation in the course of manufacture, or by the use of materials not susceptible to ageing. It is practically impossible to avoid deformation in the cold in boiler manufacture, but by a subsequent annealing of the finished parts the cold-working effect which leads to ageing can be safely eliminated. Thin-walled tubes can be subjected to a similar treatment. This treatment will obviate the use of the very expensive non-ageing material for boiler manufacture.

Mild Steel with Limited Ageing Properties. O. Bauer. (*Mitteilungen der deutschen Materialprüfungsanstalten*, 1929, Sonderheft V., pp. 12-22). The author first discusses the composition of boiler-plate material, and from the analyses of 260 specimens draws "frequency curves" showing the grouping of the figures for carbon, manganese, arsenic, sulphur, and phosphorus about certain values. He then deals with the failure of boiler plates through crushing of the material under the rivet-heads during riveting, and describes a method for testing the susceptibility of the material to this trouble. Test-pieces measuring 8×12 mm. were subjected to pressure under a special die, in such a way that one side, over a length of 33 mm., was pressed in 2 mm.; the specimens were then annealed for 2 hr. at various temperatures, their dimensions reduced to 10×8 mm. all over, a notch was cut in

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the compressed part, and a notch test made with a 10 kg.-m. pendulum. In the case of test-pieces taken from an old boiler which had failed under test after service by splitting along a row of rivet holes, the compression alone reduced the impact value to 1.8 kg.-m. per sq. cm.; in the specimens annealed at increasing temperatures the impact value decreased at first to a minimum (0.8 to 0.9 kg.-m. per sq. cm.) at 250° to 300° C., but it then rose again slowly, and at about 600° C. it returned sharply to the full value of the original material. Tests on other ordinary boiler-plate materials produced comparable curves. Experiments were also carried out on Krupp's "Izett I." mild steel, which has the following composition:

	%		%
Carbon . . .	0.13	Sulphur . . .	0.015
Silicon . . .	0.02	Copper . . .	0.19
Manganese . . .	0.58	Arsenic . . .	0.035
Phosphorus . . .	0.012		

That metal had been reported by other workers to undergo no ageing, but the new tests proved that it did in fact age; the decrease in the notch toughness and the temperature interval of the danger (low impact value) range were not so large as was the case with ordinary boiler steels. Tests on "A.-S." mild steel (made by the Press- und Walzwerk A.G., Reisholz) revealed properties superior to those of ordinary mild steel plate, but inferior to those of "Izett I." steel.

Brittleness in Mild Steel. G. R. Bolsover. (Paper read before the Iron and Steel Institute, May 1929: this Journal, p. 473).

The Oxidation of Iron and Steel at High Temperatures. L. B. Pfeil. (Paper read before the Iron and Steel Institute, May 1929: this Journal, p. 501).

Strength of Low-Carbon Steels at High Temperatures. R. G. Batson. (Engineer, 1928, Vol. 146, Dec. 28, pp. 707-709). Five samples of steel—a normalised bar, a bar cold-drawn and annealed at 650° C. for 6 hr., a superheater tube, a galvanised water-tube, and a tube nearest to the boiler fire—with carbon ranging from 0.10 to 0.17 per cent., were investigated. Preliminary tensile tests at air temperatures were followed by short-time tensile tests on the bars at from 500° to 700° C. Finally, creep tests on the bar materials at different loads and various elevated temperatures, and comparative creep tests on the bar and tube materials, were carried out. At the higher temperatures oxidation was troublesome, but this was avoided by nickel-plating the specimens—a treatment which did not affect the rate of creep. The strain-duration curves of the bar materials showed three periods: (i) An initial strain on loading followed by a rapid diminution of the rate of strain with time (due to "strain-hardening"); (ii) a period of fairly steady strain in which the creep was approximately

constant; and (iii) a final rapid increase of the rate of strain until fracture ensued. The comparative creep tests showed that the more detailed results obtained on the bar materials were representative of the tubes. The form of the stress-duration curves is briefly discussed.

Springs for Service at High Temperatures. J. R. Fritze, R. J. Sutton, and F. R. Porter. (Heat Treating and Forging, 1929, Vol. 15, Mar., pp. 301-302, 310). A search was made for a suitable steel to make springs operating at temperatures up to 600° F. Finally a high-speed steel was decided on; the composition was: Carbon 0·65, manganese 0·40, sulphur max. 0·04, phosphorus max. 0·04, silicon max. 0·30, chromium 3·5 to 4·25, vanadium 0·9 to 1·25, and tungsten 17 to 18·5 per cent. The special heat treatment necessary for this material is described. It was found that the Rockwell or scleroscope hardness tests alone were insufficient check to guard against "soft" springs, and a special deflexion test, equivalent to approximately 200 per cent. of a normal deflexion, was devised.

Recent Mechanical Tests on Steel at Higher Temperatures. A. Pomp. (Jernkontorets Annaler, 1928, Vol. 111, pp. 44-66). A review of the work of different investigators on the mechanical properties of steel up to 1000° C.

The Stability of Metals at Elevated Temperatures. C. L. Clark and A. E. White. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Apr., pp. 670-714: *see* Journ. I. and S.I., 1928, No. II. p. 399).

Cellular Structure and Hardness of Steel at High Temperatures. S. V. Belynsky. (Journal of the Russian Metallurgical Society, 1928, No. 3, pp. 137-146). (In Russian.)

Introduction to the Study of the Mechanical Properties of Metals as a Function of Temperature. J. Galibourg. (Mémoires de la Société des Ingénieurs Civils de France, 1928, Vol. 81, Nov.-Dec., pp. 1273-1295).

The Elastic Limit of Steel at High Temperatures. F. Körber. (Stahl und Eisen, 1929, Vol. 49, Feb. 28, pp. 273-277).

Some Mechanical Properties of Cast Steel at High Temperatures. (Metallurgist, 1929, Mar., p. 43). A brief abstract of a paper by Körber and Pomp (*see* Journ. I. and S.I., 1928, No. II. p. 401).

The Mechanical Properties at High Temperatures of Drawn Steel Wire, in Relation to the Degree of Drawing, the Temperature of

Drawing, and the Carbon Content. A. Pomp and W. Knackstedt. (Stahl und Eisen, 1928, Vol. 48, Dec. 6, pp. 1705-1712 : see Journ. I. and S.I., 1928, No. II. p. 400).

Increasing the Endurance of Steel Parts (of Machines) by Pressing the Surface (Work-Hardening). O. Föppl. (Stahl und Eisen, 1929, Vol. 49, Apr. 25, pp. 575-577). The author shows that the endurance of steel parts, such as crankshafts, may be increased by compression of the surfaces rather than by polishing. High polishing is practised in the belief that thereby the risk of incipient cracks is minimised, but to compress the surface by a process of reeling has a greater effect in prolonging the resistance of a steel shaft to the effect of torsional and bending vibratory stresses. Long-time alternating stress tests were carried out on compressed and uncompressed crankshafts, and in most cases the compressed material withstood more than double the number of stress reversals than the uncompressed. Tables show the comparative results.

A High-Speed Endurance Testing Machine for Leaf Springs. J. Bradley. (Engineering, 1929, Vol. 127, Jan. 11, pp. 36-37). The machine described, which is intended for testing single plates from leaf springs, was built by the National Physical Laboratory in order to carry out researches on the properties of laminated springs on behalf of the Springs Research Committee of the Department of Scientific and Industrial Research.

Fatigue Testing Machines. W. Deutsch and G. Fiek. (Zeitschrift des Vereines deutscher Ingenieure, 1928, Vol. 72, Dec. 1, pp. 1760-1764). Various machines for making fatigue tests are illustrated and described ; the stressing of the test-pieces is brought about by impact and vibration applied to tensile, compressive, combined tensile-compressive, bending, and torsional tests.

The Principles of the Theory of the Strength of Materials. M. Ensslin. (Zeitschrift des Vereines deutscher Ingenieure, 1928, Vol. 72, Nov. 10, pp. 1625-1634). The author summarises modern ideas on fatigue, and discusses the significance of the limit of proportionality, the elastic limit, and the yield point.

Elastic Limit and Yield Stress. (Metallurgist, 1929, Vol. 5, Jan., pp. 12-13). An abstract of the above paper.

Fatigue Fracture and the Permissible Load on Roller Bearings. R. Mundt. (Zeitschrift des Vereines deutscher Ingenieure, 1929, Vol. 73, Jan. 12, pp. 53-59). The failure of roller bearings through fatigue is discussed, and the calculation of the maximum load permissible is carried out. The calculation applies only to static loading.

Elastic Failure and Fatigue Failure of Metals. H. F. Moore. (Paper read before the American Association for the Advancement of Science (Section M, Engineering), Dec. 28, 1928: *Mechanical Engineering*, 1929, Vol. 51, Apr., pp. 290-294). The author gives a number of examples of elastic and of fatigue failure, indicates the essential differences between the two types of failure, and stresses their importance in structural and machine design.

Determination of Endurance Limits. (Metallurgist, 1928, Vol. 4, Dec. 28, pp. 187-189). An abstract of an article by J. Geller (*Archiv für das Eisenhüttenwesen*, 1928, Vol. 2, Oct., pp. 257-260: see *Journ. I. and S.I.*, 1928, No. II, p. 398).

The Relative Safeties of Mild and High-Tensile Alloyed Steels under Alternating and Pulsating Stresses. B. P. Haigh (*Chemistry and Industry*, 1929, Vol. 48, Jan. 11, pp. 23-30). The author reviews and discusses a wide variety of tests and experiments with alternating and pulsating stresses to illustrate and contrast the conditions in which fatigue cracking may be a source of danger. It is shown that the relation between the fatigue strength and yield strength of mild steel is such that fatigue cracking is necessarily uncommon in mild steel with ordinary conditions of loading. In high-tensile steels the relation between the two kinds of strength is often such that fatigue cracking is more frequent.

What Happens in Couplings: Fatigue of Materials—What it is and how it Occurs in Flexible Couplings. H. F. Moore. (*Iron and Steel Engineer*, 1928, Vol. 5, Dec., pp. 513-517). The subject is treated under the following headings: Common misconceptions concerning fatigue; slip in metals; effect of reversing stresses; function of flexible couplings; stresses in the flexible members; fallacy of stored energy; fatigue limit and energy-storing capacity for various metals; elimination of flexible materials; refinement of design; commercial application of the floating sleeve principle; oil as a load-carrying agent; and necessity for alignment couplings.

The Process of Making Steel and the Characteristics of Resistance to Alternating Stresses. R. Cazaud. (*Aciers Spéciaux*, 1929, Vol. 4, Jan., pp. 14-22). The author puts forward test results to show the influence of the mode of manufacture of steel on its mechanical properties in general and on its resistance to alternating stresses in particular. In order to avoid defects in steels due to fatigue, and to attain greater safety, he advocates the selection of various types and qualities of steels and their submission to a large number of tests of the repeated stress, rotating flexion, impact, and vibratory types.

Remarks and Simple Experiments on Latent Stresses in Metals. A. Portevin. (*Revue de Métallurgie, Mémoires*, 1929, Vol. 26, Feb., pp. 68-75). The author discusses some of the phenomena observed which are due to stresses within the metal.

X-Ray Investigation of the Internal Stress of Carbon Steels. S. Sekito. (*Science Reports of the Tôhoku Imperial University, Sendai*, 1928, Vol. 17, pp. 1227-1236). The broadening of the spectral lines by the action of cold-working previously found in the case of copper has also been confirmed in the case of carbon steels. The maximum percentage variation of the lattice constant was 0.4, and the corresponding internal stress 84 kg. per sq. mm., which is a little lower than the tensile strength in these steels. This confirms Honda's view that the internal stress can never exceed the tensile strength of the specimen.

Method of Thermal Colouring for Determination of Local Internal Stresses in Iron and Steel. A. F. Golovin. (*Journal of the Russian Metallurgical Society*, 1928, No. 3, pp. 89-92). (In Russian.)

The Detection of Internal Stresses in Rods and Tubes. G. Sachs. (*Mitteilungen der deutschen Materialprüfungsanstalten*, 1929, Sonderheft V., pp. 138-144). See *Journ. I. and S.I.*, 1927, No. II. p. 603.

Gases Extracted from Iron-Carbon Alloys by Vacuum Melting. N. A. Ziegler. (*American Institute of Mining and Metallurgical Engineers*, 1929, Technical Publication No. 168). The present paper is a continuation of the work on gas analysis described in *Proceedings of the Institute of Metals Division*, 1928, p. 544. A series of iron-carbon alloys with carbon ranging from 0.0038 to 4.45 per cent. was prepared in a magnesia-lined graphite crucible placed in a high-frequency furnace. The alloys were remelted in a bell-jar vacuum furnace, the gases given off being collected and analysed. The conclusions are as follows: water vapour is given off by low-carbon laboratory alloys and by steels, but not by high-carbon alloys and cast irons. The amount is very small. Carbon dioxide is evolved in relatively small quantities in all samples. Carbon monoxide is the principal constituent of the gaseous mixtures in all cases. The amount increases very rapidly with the increase of carbon in the original sample. Free oxygen is given off by all samples in negligible quantities. Hydrogen is not evolved by the laboratory samples and by the cast irons, but to a small extent by open-hearth steel. A certain iron-carbon alloy (about 0.07 per cent. carbon for this particular series) contains just enough carbon and oxygen to be very nearly decarburised and deoxidised by the vacuum melting, as judged from the results of the chemical analysis and the metallographic examination. Commercial alloys have the same characteristics, so far as gas evolution is

concerned, as the laboratory samples of the same carbon content. The number of inclusions decreases uniformly with the increase of the carbon content.

Technical Properties of Vacuum-Melted Metals. W. Rohn. (*Zeitschrift für Metallkunde*, 1929, Vol. 21, Jan., pp. 12-18). The author first reviews the earlier proposals for the treatment of metals for technical purposes by submitting them to vacuum treatment without the application of any further heat. Vacuum melting in furnaces which were not thoroughly air-tight was virtually a refining process, and results were only possible under practically completely air-tight conditions. The author next discusses gases in metals, and the evolution of gases from molten metals *in vacuo*, and then reviews the linings used in vacuum melting, and their improvement. He indicates some of the products which are to-day made in technical quantities, giving furnace sizes and weights of charges; he also records outputs from 1917 to 1928.

Oxygen in Steel. L. Persoz. (*Aciers Spéciaux*, 1928, Vol. 3, Nov., pp. 259-262).

Nitrogen in Steel. B. Svechnikoff. (*Journal of the Russian Metallurgical Society*, 1928, No. 1., pp. 35-58). (In Russian.)

Action of the Principal Elements Added to Steels. L. Persoz. (*Aciers Spéciaux*, 1928, Vol. 3, Nov., pp. 249-255). The author notes briefly the properties conferred on steel by the presence of the various elements present in or added to steels.

Influence of Added Elements on the Properties of Steels. L. Persoz. (*Aciers Spéciaux*, 1929, Vol. 4, Jan., pp. 69-74). The iron-carbon diagram and the variations in the properties of steel due to the presence of various amounts of carbon are discussed.

Influence of Tin on the Quality and in Particular on the Ability to Roll of Open-Hearth Mild Steel. W. Keller. (*Stahl und Eisen*, 1929, Vol. 49, Jan. 31, pp. 138-139). The results of an investigation are reported on the influence of tin on the properties of mild steel and also on its forging and rolling qualities. Tin was added to open-hearth steel during teeming, and a series of blooms was produced, with tin ranging from 0.23 to 1.0 per cent. The tensile strength increased from 27 to 35 tons per sq. in. over that range of tin content, and the elongation fell from 24 to 16 per cent. Rolling tests showed that steel with 0.60 to 0.70 per cent. of tin would roll into sheets without cracking at the edge. Steel with up to 0.60 per cent. of tin forged fairly well and withstood the cold bending test perfectly. At higher percentages of tin the forgeability fell off. The author considers that the bad effect of tin on steel has been overrated.

Zirconium in Steel. L. Persoz. (*Aciers Spéciaux*, 1928, Vol. 3, Nov., pp. 256-258). The properties of zirconium and of zirconium steel are discussed, and methods for estimating the element in steel and in ferro-zirconium are given.

Alloy Cast Steels. D. Zuege. (Paper read before the American Foundrymen's Association, Apr. 1929). The author presents data showing the physical properties of some alloy steels specially adapted to foundry use. The steels considered are: Vanadium steel 1.20 to 1.60 per cent., manganese steel 0.75 to 1.00 per cent., chromium steel (carbon 0.35 to 0.45 per cent.), chromium-nickel steel (carbon 0.40 to 0.50, chromium 0.75 to 1.00, nickel 1.00 to 1.50 per cent.), and chrome-nickel-molybdenum steel.

High-Duty Cast Chrome-Nickel Steel. V. Zsák. (*Die Giesserei*, 1929, Vol. 16, Mar. 1, pp. 193-205). A record of an investigation of the properties of a cast nickel-chrome steel in various conditions of heat treatment. The specification of the metal was carbon 0.28 to 0.35, manganese 0.50, silicon 0.2 to 0.3, chromium 0.55 to 0.95, and nickel 3 to 3.75 per cent.; the phosphorus and sulphur were to be as low as possible, and not to exceed 0.04 per cent.

High-Carbon High-Chromium Steels. J. P. Gill. (*Transactions of the American Society for Steel Treating*, 1929, Vol. 15, Mar., pp. 387-428). The author compares the properties of six steels of the high-carbon high-chromium type which find use in the manufacture of dies. The comparison covers the critical points, hardening and tempering curves, microstructure, and physical properties. A short discussion of the constitution of these steels is also included, together with a brief historical outline of their development.

An Investigation of the Physical Properties of Certain Chromium-Aluminium Steels. F. B. Lounsberry and W. R. Breeler. (*Transactions of the American Society for Steel Treating*, 1929, Vol. 15, May, pp. 733-766). The authors have investigated the physical properties of steels containing 2 to 6 per cent. aluminium and 7 to 13 per cent. chromium, with silicon and carbon varying up to approximately 1 per cent. maximum. The effect of the addition of small amounts of nickel, cobalt, molybdenum, vanadium, manganese, tungsten, and copper was also studied. The properties investigated were: (1) Effect of thermal treatment on hardness and microstructure; (2) resistance to oxidation at elevated temperatures; (3) resistance to atmospheric corrosion; (4) forgeability; (5) tensile strength at normal and elevated temperatures; and (6) impact values. These alloys possess high critical ranges and a very stable α phase, the stability of which increases with increase in the aluminium, chromium, and silicon contents. Steels containing about 5.5 per cent. aluminium,

9.5 per cent. chromium, 1 per cent. silicon, and 0.50 per cent. carbon were dominantly ferritic at all temperatures. Depending on the total aluminium, chromium, and silicon contents, these alloys exhibit complete resistance to oxidation at temperatures from 1550° to 1850° F.

Hadfield Steel—Its Physical Properties in Connection with Heat Treatment and Microstructure. V. Svechnikoff. (Journal of the Russian Metallurgical Society, 1929, No. I., pp. 23–38). (In Russian.)

Copper Steels with High Carbon Content. A. F. Stogoff and W. S. Messkin. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 321–331). The results of a research on the physical and mechanical properties of steels containing from 1.19 up to 5.07 per cent. copper with carbon from 0.74 to 1.22 per cent. are reported. Heating and cooling curves were taken and the expansion was measured with a Chevenard dilatometer; the electric conductivity was measured; the microstructure was examined in the annealed and hardened and tempered states; magnetic tests were made; and, finally, tensile tests under different conditions of heat treatment were carried out. The A_{r1} point is lowered by adding copper, but the pearlite content is not affected. Copper does not increase the hardness of steel, but it does increase the coercive force and field strength without affecting the remanence. The elastic limit, ultimate strength, and hardness all increase with increasing copper; but the elongation, reduction of area, and notch toughness fall off. In the quenched and tempered state copper steels show high tensile properties, with good elongation and reduction of area.

High-Strength Structural Steels. E. E. Thum. (Iron Age, 1929, Vol. 123, Mar. 21, pp. 797–800). The author outlines the characteristic properties of high-strength steels for boilers, rails, structures, ships, and gas cylinders. In American practice nearly all the tonnage steels now contain more than the 0.30 per cent. of manganese necessary for soundness, and the medium and hard grades are essentially alloys of iron, carbon, and manganese. Open-hearth rail practice has developed along somewhat the same directions that have produced the high-strength structural steels—at least, to the extent that they both carry 0.20 to 0.30 per cent. of silicon. For structural purposes the American engineers prefer higher carbon and lower manganese than do English constructors. In America chemical limits would run carbon 0.30 to 0.45, silicon 0.15 to 0.45, and manganese 0.70 to 1.10 per cent. Greater strength can be obtained more safely by higher manganese than by higher carbon. The properties of British steels used for shipbuilding are compared, and the superiority of “D” quality steel, containing carbon about 0.33 per cent., silicon about 0.12 per cent., and manganese 1.1 to 1.4 per cent., is shown. The chemical

composition and properties of Freund steel produced in Germany are also shown.

Silicon-Manganese Steels with Chromium Additions for Engineering Applications. A. B. Kinzel. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 866-876). The author deals with silicon-manganese steels of medium carbon content, which are highly suitable for engineering purposes and are susceptible to heat treatment. The addition of a hardening element, particularly 1 per cent. of chromium, increases the susceptibility to heat treatment and ease of application of heat treatment. The physical properties of the silicon-manganese-chromium steels are superior to those of the silicon-manganese or straight manganese steels, and of the same order as those of the best alloy steels similarly heat-treated.

High-Tensile Structural Steels. H. Buchholz. (Forschungen und Fortschritte, 1929, Jan. 20; Metallurgist, 1929, Vol. 5, Feb., pp. 29-30). The author describes the properties of a new high-tensile steel, and compares them with those of other steels of the same class. The new material has the normal carbon content of a mild structural steel; it contains in addition a little chromium and about 1 per cent. of copper. It is stated to have the same good physical properties as silicon steel (yield stress over 23 tons per sq. in., tensile strength 33 to 40 tons per sq. in., elongation about 20 per cent.). The amount of scrap made with this steel is low, so that, despite the use of expensive additions, it can be produced more economically than silicon steel. It is easy to weld, and is less subject to corrosion than ordinary carbon steel.

Mechanical Properties of British Rail Steels. W. E. Dalby. (Minutes of Proceedings of the Institution of Civil Engineers, Session 1928-1929, Vol. 227, Part I.). This is a continuation of the work described in the author's paper on "Mechanical Properties of Steel," (Ibid., 1926, Vol. 221, p. 21), and deals specially with the mechanical properties of steels used for rails on British railways.

Investigation of the Influence of the Rolling Temperature on the Properties of Rails. R. Stumper. (Stahl und Eisen, 1929, Vol. 49, Feb. 7, pp. 177-187). All recent efforts for the improvement of the strength properties of rails have been based on changes in the chemical composition, such as by increasing the carbon to 0.88 per cent., or by raising the manganese to 2.2 per cent. An addition of silicon up to 0.6 per cent. was found to improve the elastic limit, but the difficulty of rolling such rails has proved a disadvantage. Better success has been obtained with manganese-silicon steel rails, with carbon 0.3 to 0.6, silicon 0.3 to 0.6, and manganese 1 to 1.5 per cent. The present author has now investigated the effect of controlling the rolling temperature at the various stages of rolling ordinary basic Bessemer rails, with

carbon 0.38 to 0.45, silicon 0.06 to 0.15, manganese 0.91 to 1.13, phosphorus 0.05 to 0.07, and sulphur 0.04 to 0.05 per cent. A low finishing temperature, not exceeding 950° to 1000° C., has the most beneficial effect, both on the grain-size and on the tensile properties. The mean results of a large number of tests show that with finishing temperatures of 950° and 1150° C. the strength of the material in the head of the rail was :

Temperature. ° C.	Elastic Limit. Tons per sq. in.	Yield Point. Tons per sq. in.	Elongation. %
950	26.5	46.3	15.0
1150	24.7	45.0	14.6

Similar results were obtained for the web and foot of the rail.

Influence of Rolling Temperature on the Properties of Rails. R. Stumper. (Iron and Coal Trades Review, 1929, Vol. 118, Mar. 22, p. 441). An abridged English translation of the above article.

The Properties of Basic Bessemer Rail Steel. J. W. Reicherts and A. Wimmer. (Stahl und Eisen, 1929, Vol. 49, Mar. 21, pp. 385-388). Comparative tests have been made on basic Bessemer and open-hearth rail steel, the results of which are held to indicate that the claim for the superiority of open-hearth steel over basic Bessemer steel as a material for rails is exaggerated. The basic Bessemer steel had the following composition: carbon 0.40 to 0.48, silicon 0.14 to 0.28, manganese 0.87 to 0.97, phosphorus 0.022 to 0.054, sulphur 0.032 to 0.38 per cent. The tensile tests on the material as rolled gave elastic limit 34.6 to 39.3, and breaking stress 65.3 to 74.6 kg. per sq. mm., with elongation 18 to 16.6, and reduction 39.3 to 30.4 per cent. After normalising, these values were all slightly improved. The open-hearth steel had carbon 0.46 to 0.47, silicon 0.28 to 0.26, manganese 0.78 to 0.67, phosphorus 0.028 to 0.022, sulphur 0.035 to 0.032 per cent. The tensile properties were much the same as those of the basic Bessemer steel. The results of wear tests in the Amsler machine were slightly better in the case of the open-hearth rails. The point of chief importance in regard to the basic Bessemer steel is that it should be properly deoxidised in the process of manufacture. The deoxidisers and carburisers should be added in liquid form, and a low teeming temperature with additions of ferro-silicon ensure a good evolution of gas. Such steel will make good hard rails which will meet the present-day conditions of service in every respect as well as the open-hearth rails.

Chemical Composition of Rail Steels. E. Houbaer. (Revue Universelle des Mines, 1929, Series 8, Vol. 1, Jan. 15, pp. 36-43). A practical study of the various elements generally entering into the chemical composition of rail steels.

Medium-Manganese Rail a Success. E. E. Thum. (Iron Age, 1929, Vol. 123, Apr. 4, pp. 940-942). It is shown that the standard American open-hearth carbon steel rail can be measurably improved by lowering the carbon to 0.55 to 0.70 per cent., and increasing the manganese to 1.25 to 1.50 per cent. Rails of this composition have a long life and are almost entirely free from transverse fissures.

On a Point of History Concerning the Invention of High-Speed Steels. L. Demozay. (Revue de Métallurgie, Mémoires, 1929, Vol. 26, Mar., pp. 115-116). The author draws attention to a contribution by Cox to the discussion of a paper by Hoyt (*see* Journ. I. and S.I., 1928, No. II. p. 419). It is pointed out that the original inventor of high-speed steel was H. A. Brustlein, a Frenchman. The author adds additional information bearing out this assertion.

Effect of Hardening Temperatures and Annealing on Cutting Efficiency of High-Speed Steels. E. Kothny. (Maschinenbau, 1928, Vol. 7, Oct. 18, pp. 959-966).

Cutting Qualities of an Alloy Steel as Influenced by its Heat Treatment. O. W. Boston and M. N. Landis. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Mar., pp. 451-473). The results of a series of experiments made to determine the value of four methods of estimating a machinability rating of an S.A.E. 6140 steel under various heat treatments are presented. The cutting qualities are expressed in four ways: a cutting rating as influenced by the tool life and finish secured, as observed while a turning tool was cutting under standardised conditions, the torque and thrust of a $\frac{3}{4}$ -in. drill cutting under standardised conditions as measured on a drill dynamometer, and the time taken by a $\frac{1}{4}$ -in. drill to penetrate $\frac{1}{4}$ in. while cutting under standardised conditions. The materials were given a number of single and double heat treatments so as to obtain various annealed structures, as well as various degrees of spheroidising. It is shown that pure annealing does not give the best machining qualities, but that steels cut best when the spheroidising is greatest.

Cutting Tools Research Committee. Report on Machinability. E. G. Herbert. (Proceedings of the Institution of Mechanical Engineers, 1928, No. II., pp. 775-825). Machining processes change the physical properties of metals to which they are applied. No quantitative relationship can therefore exist between the machinability of metals and the physical properties which they originally possess and which have not been changed by machining. Since metals differ in their capacity for being hardened by deformation, and machining processes differ in respect of the degree of deformation they produce, machinability is not an attribute of metals which can be considered or measured apart from particular machining processes. The hardness of the chips removed by

a metal-cutting process indicates the hardness induced in the metal by that process. It takes account of both the characteristics of the metal and the character of the machining process, and is a measure of machinability. The original hardness of metals gives no indication of machinability. The maximum induced hardness measured by the pendulum work-hardening test gives a general indication in the case of ductile metals, but none in the case of brittle metals. No quantitative relationship exists between the speed at which a metal can be cut, the resistance it offers to the cutting tool, and its blunting effect on the tool. Very soft steel offers greater resistance to cutting and has a greater blunting effect on the tool than similar steel which has been made harder by heat treatment. This may be attributed to the less efficient natural cutting angles of the built-up edge formed in cutting the softer steel. Highly efficient natural cutting angles have, however, been found, and highly efficient cutting obtained, in soft wrought iron.

The Machinability of Special Steels. T. Wickenden. (*Aciers Spéciaux*, 1928, Vol. 3, Jan., pp. 13-20; *Stahl und Eisen*, 1929, Vol. 49, Jan. 3, pp. 20-21). Trials as to the machinability of carbon steels, chromium steels, and nickel steels were made by the author to determine the best cutting speed in relation both to the tensile strength of the material and the chemical composition. In Taylor's classic experiments the tensile properties alone were taken into consideration without regard to other conditions. With a nickel steel with 0.26 per cent. carbon and a tensile strength of 41 tons to the sq. in., a cutting speed of 78 m. per min. was practicable, but with a carbon steel containing 1.05 per cent. carbon and a tensile strength of 40 tons a cutting speed of only 44 m. per min. could be maintained. This is due to the destructive effect of the carbides on the cutting edge of the tool, and the tensile strength is not a regular criterion of the cutting speed that could be used on a material. The author also found that the quality of the surface is not only dependent on the cutting speed but on the rate of feed and cutting angle, and that for every kind of steel there is a definite critical range of speed at which cutting leaves a rough surface. Below and above that range a good surface can be obtained.

Questions of Materials and Hardness in the Manufacture of Tools. (Kruppsche Monatshefte, 1928, Vol. 9, Oct., pp. 147-159). The following subjects are dealt with: Classification of tool steels; hardening; hardening faults and deformation during hardening; high-speed steels; hardening high-speed steels; tempering high-speed steels; wear-resistance of high-speed steels. One large table gives a list of tool steels and their applications, their analyses, strengths, and hardnesses, and the methods of hardening them. A second table collects together hardening faults, their causes, the appearance of the fractures and the remedies. A third table comprises the analyses and heat treatments of the three classes of German special steels; class B

contains less than 13.5 per cent. of tungsten, class A contains 13.5 to 18 per cent. of tungsten but no vanadium, molybdenum or cobalt, and class C contains either more than 18 per cent. of tungsten, or, if that metal is present in less amount, additions of the above three special elements must be made.

Tool Steels of the Chemical Analyses shown have given Excellent Service. E. E. Thum. (Iron Age, 1928, Vol. 122, Nov. 22, p. 1286). The author lists a number of chemical analyses of American tool steels which will give excellent service for the class of work indicated.

English and American Die Tool Steels. J. W. Urquhart. (Heat Treating and Forging, 1929, Vol. 15, Feb., pp. 177-182). A review contrasting the compositions, and the hardening, tempering, and general thermal treatments employed in the two countries.

The Properties of Cold-Drawn Wires, with Particular Reference to Repeated Torsional Stresses. F. C. Lea and R. A. Batey. (Proceedings of the Institution of Mechanical Engineers, 1928, No. 11., pp. 865-899). The results are given of an investigation of carbon steel wire. The experiments show that the resistance of cold-drawn wires to repeatedly applied shear stresses is very much less than would be expected from the static properties of the wire. The fatigue range may be less than 0.18 of the static breaking stress in tension, and 0.23 of the torsional strength. Heavy cold-work which produces high static resistance damages the material at the surface of the wire. Under the action of repeated stresses cracks commence at the surface. The behaviour of the wires under repeated torsional stresses can be greatly improved by low-temperature heat treatment. The authors consider that torsional fatigue tests are the most satisfactory, if not the only satisfactory, method of investigating the fatigue properties of wire.

The Deterioration of Colliery Winding Ropes in Service. S. M. Dixon, M. A. Hogan, and J. M. Robertson. (Mines Department, Safety in Mines Research Board, Paper No. 50, 1928). The authors review the various factors which operate to cause the deterioration of winding ropes in service, and describe a number of typical failures. The results of the observations summarised in the paper emphasise the fact that failures of winding ropes are seldom attributable to a single cause, but are frequently the result of the simultaneous operation of a number of influences. Three causes influence the deterioration of winding ropes, namely, repeated stress, wear, and corrosion. Fatigue or failure by slow fracture was found to be the most common influence. It also appeared to be the most dangerous, because of the uncertainty in its incidence, depending as it does on the effects of kinetic stresses and on the resistance of cold-drawn wire to repeated stress, a

phenomenon about which little is known. The examinations, in addition to proving the necessity for recapping at short intervals, showed the advisability of cutting off several feet of rope at each recapping, and emphasised the importance of careful examination of the portion cut off to ascertain its internal condition, as an indication of the possible conditions existing elsewhere in the rope.

Note on the Rupture of a Steel Haulage Cable of the Locked Cable Type. De Bere. (*Annales des Mines*, 1929, Vol. 15, pp. 88-92). Details of the life of the cable and of tests made during its period of use and after its failure are given, and the cause of the rupture discussed. It is pointed out that in the locked cable type there is a greater proportion of wires hidden from view, and therefore great attention should be paid to any indications of likely failure given by the outside wires.

Methods for Mechanically Testing Lifting Gear in Service, such as Chains, Ropes, &c. K. Grocholl. (*Die Giesserei*, 1928, Vol. 15, Dec. 7, pp. 1232-1233). The author stresses the importance of testing periodically appliances which have to raise heavy loads. He then describes various methods by which such articles as chains, cables, ropes, &c., may be tested in the works where they are situated, using only such means as are ready at hand.

Experiments with Wire Cables and Pulleys for the Niederfinow Ship-Canal Lift. A. Freund. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Jan. 19, pp. 73-81). For the purpose of the experiments described a special test tower was erected; cables, bearings, pulleys, and other appliances for use in the new ship-canal lift at Niederfinow were subjected to full-size tests, and the strength under conditions of starting-up and of motion were determined by means of special new apparatus.

Light on the Wire Rope Question. R. Woernle. (*Zeitschrift des Vereines deutscher Ingenieure*, 1929, Vol. 73, Mar. 30, pp. 417-426). The author stresses the need for systematic long-time tests on wire ropes. He then deals with the influence of various factors (the radius of the wheel groove, the spin of the rope, loading of the rope, the thickness and strength of the rope) on the life of lift and crane ropes, the stretch of the rope in service, the influence of the number of flexions and of broken wires on the reduction of the load-bearing capacity of the rope. The author then turns to ropes with long life, and discusses the effect of galvanising and other factors on the life. He also considers the chemical analysis and various tests for rope wires.

Testing Compressed-Gas Cylinders. G. D. Bagley. (Paper read before the Compressed Gas Manufacturers' Association: Iron Age,

1929, Vol. 123, Apr. 18, pp. 1067-1069). A method is described for testing compressed-gas cylinders whereby the wall thickness and ductility are automatically determined. The volume expansion is measured at two pressures, and a curve-drawing machine records data for each cylinder.

Gas Cylinders. (Department of Scientific and Industrial Research : Third Report of the Gas Cylinders Research Committee, London, 1929). The results of tests are reported on the properties of nickel steel and nickel-chromium-molybdenum steel to determine their suitability for the manufacture of light gas cylinders.

The Mechanical and Metallurgical Properties of Spring Steels as Revealed by Laboratory Tests. G. A. Hankins and Miss G. W. Ford. (Paper read before the Iron and Steel Institute, May 1929 : this Journal, p. 217).

The Effect of "Nip" on the Mechanical Properties of Laminated Springs. R. G. Batson and J. Bradley. (Department of Scientific and Industrial Research, 1928, Engineering Research Special Report No. 11). In the manufacture of laminated springs it is sometimes the practice to vary the curvature of the individual plates of the spring in such a way that when the leaves are placed on one another there are gaps between them. The leaves are clamped together, usually by a bolt through the centre. The leaves are thus pulled to approximately the same radius of curvature, and the load required for the purpose varies according to the gaps which have been left initially between the leaves. Laminated springs made in this way are said to have been given "nip." The assembly of the leaves in springs of this kind produces stresses in the longer leaves of the opposite sign to that which is imposed by the load, and thus the maximum stress in these leaves is reduced. In order to investigate the effect of "nip" on the behaviour of laminated springs, two sets of springs were tested. Each set consisted of three springs—one with very little nip, the second with moderate nip such as is used in practice, and the third with excessive nip. The springs were made from a straight carbon steel, water-hardened, of the following composition: 0.63 carbon, 0.093 silicon, 0.70 manganese, 0.044 sulphur, and 0.059 per cent. of phosphorus. The advantage of nip is that, if it is adjusted correctly, the master leaf when under repeated loadings has zero mean stress, and is, therefore, in its most favourable condition for resistance to repeated stresses. It is shown that even with springs having so-called "moderate" nip, this amount of nip is greatly in excess of the theoretical requirements. Increase of nip increases the mean stress in the short leaf, while the range of stress is approximately constant. Owing to the fact that the master leaves were thicker than the other leaves, the actual range of stress in the master leaves was greater than

that in the short leaves. This compensates to some extent for the increased mean stress in the short leaves. The ranges of stress at which fracture occurred are lower than the safe ranges which would be expected from a consideration of the endurance of a similar material tested in the form of machined test-pieces.

Static and Endurance Tests of Laminated Springs made of Carbon and Alloy Steels. R. G. Batson and J. Bradley. (Department of Scientific and Industrial Research : Engineering Research, 1929, Special Report, No. 13). The report describes an investigation of the endurance of laminated springs and the stress which can be allowed on the spring leaves. It forms a continuation of the work on the effect of "nip" (Special Report, No. 11). Tests were carried out on springs made from 0.6 per cent. carbon steel, silico-manganese steel, and chromium-vanadium steel, and on springs of the 6-leaf design made from various carbon and alloy steels. The following tests were carried out : (a) static load-deflection observations ; (b) determination of the stresses on the master leaves of the springs when the latter are under load ; and (c) endurance tests. The results which are presented, by means of tables and graphs, suggest a probable explanation of the fractures of laminated springs in practice, in the very low limiting ranges of stress obtained from the springs compared with those obtained from the materials in the form of turned and polished specimens, upon which no doubt the data of design have been hitherto based. Further investigation is being undertaken to determine the reasons for the wide difference revealed.

Investigation of a Fractured Boiler End. O. Laue. (Glückauf, 1928, Vol. 64, Dec. 15, pp. 1684-1686). The author describes an investigation, and its results, into the failure of a boiler-end which fractured under test after eight years' service. The fracture was intergranular, and from the microscopic and Fry's etching test evidence it was concluded that the material had been cold-worked beyond the yield point.

Testing of Materials and Car Parts. C. A. McGroder. (Iron Age, 1929, Vol. 123, Mar. 28, pp. 876-878). An illustrated account is given of the equipment and methods used at the plant of Chrysler Motors for the testing of automobile parts. Shock, torsion, and bursting tests are used.

Characteristics of Auto-Body Sheets. R. C. Todd. (Iron Age, 1929, Vol. 123, Apr. 11, pp. 1006-1008). Particulars are given of the various grades of automobile sheets produced in America.

A Study of the Structure and Mechanical Properties of Sheet Iron as Influenced by the Thermal Treatment. G. N. Cholmogorov. 1929—i.

(Journal of the Russian Metallurgical Society, 1928, No. III., pp. 72-88). (In Russian.)

The Testing of the Materials of Tubes, with Reference to the Latest Processes. (Röhrenindustrie, 1928, Vol. 21, Dec. 6, pp. 493-495). Owing to the increased performances expected of modern tubes, the testing of the materials and of the finished articles is of great importance; various tests applicable particularly to tubes are mentioned.

Considerations on Tubes used in Bicycles and Motor Bicycles. (Röhrenindustrie, 1929, Vol. 22, Feb. 28, pp. 67-68). The mechanical properties of steels used for the manufacture of bicycles and motor bicycles are discussed. Possible sources of failure are pointed out; improper annealing may leave sufficiently great internal stresses in the tubes so that cracks are started when the joints are brazed. The stresses imposed on the finished machines are alternating in character, and anything likely to give rise to "notch action" must be avoided.

Steel Failures in Aircraft. F. T. Sisco. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Apr., pp. 589-629). The author discusses failures in steel aircraft parts that have been investigated by the U.S. Air Corps at Dayton, Ohio. The methods used in the investigation are briefly described, and a classification is given of the various failures in respect to their origin. Typical cases are given of: (1) Failures due to faulty methods of manufacture and not caused by defective material; (2) failures due to internal defects such as non-metallic inclusions; (3) failures due to seams and other surface defects; (4) miscellaneous failures due to defective steel, including large grain-size, segregation, and banding; (5) failures due to faulty or wrong heat treatment; and (6) failures due to welding.

Special Steels in Aircraft Construction. H. Hoffmann. (Röhrenindustrie, 1928, Vol. 21, Nov. 22, pp. 475-476).

SPECIFICATIONS.

British Standard Specification for Tramway Tyres. (British Engineering Standards Association, 1929, Report No. 101).

American Specifications for Foundry Pig Iron, Grey Iron, Malleable Iron, and Steel Castings. O. Schliewiinsky. (Die Giesserei, 1929, Vol. 16, Mar. 22, pp. 267-274). A translation into German of specifications issued by the U.S. Bureau of Standards Federal Specification Board.

MAGNETIC AND ELECTRICAL PROPERTIES OF IRON AND STEEL.

The Magnetic and Electrical Properties of Cast Iron. (Zeitschrift für die gesamte Giessereipraxis, 1927, Vol. 48, Dec. 11, pp. 425-426).

Alloys of Iron with Physical Peculiarities. F. Stäblein. (Kruppsche Monatshefte, 1928, Vol. 9, Dec., pp. 181-189). The magnetic properties, the coefficient of expansion, and the electrical resistance of iron and of various alloys of iron are discussed.

The Influence of Cold-Deformation and of Heat Treatment on the Electrical Conductivity of Copper, Aluminium, and Iron. P. Bardenheuer and H. Schmidt. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 193-212).

What is the Magnetic Permeability of Iron ? T. D. Yensen. (Journal of the Franklin Institute, 1928, Vol. 206, Oct., pp. 503-510). The author reviews the values for the magnetic properties of iron which have been progressively obtained since 1870. The changes in the values recorded are due to the increasing ability to produce purer metal, and finality is not yet reached. The latest (1928) values are as follows: initial permeability, 1150; max. permeability, 61,000; hysteresis loss, 300 ergs per c.c. per cycle for $B = 10,000$ gauss.

Magnetic Investigations of Carbon Steel. C. C. Duell. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Apr., pp. 630-651). The author reports the results obtained by magnetic methods in an investigation of irons and steels of various carbon contents and in various conditions. It was found that in steels containing cementite a drop in magnetism occurs from 150° to 220° C. The author sets forth the hypothesis that carbon is soluble in α -iron but carbide is not. In steels containing only martensite decreased magnetism occurs at 300° C. Martensite is defined as a crystalloid material which results when a solid solution in γ -iron is cooled at such a rate as to permit the γ -iron to transform to α -iron, but not to permit the alloying element to form a chemical compound or a solid solution as the case may be. Cementite is stated to be a stable compound at all temperatures below 745° C., and with a proper carburising heat treatment below this temperature, iron may be converted entirely into carbide.

The Magnetostriction of Various Steels. J. S. Rankin. (Journal of the Royal Technical College, 1929, Vol. 2, Part I., Jan., pp. 12-19). A method of finding the alteration in length of various steels when subjected to magnetizing forces is described, the small changes involved being measured by oscillating thermionic valves.

Apparatus for Thermomagnetic Analysis. R. L. Sanford. (Bureau of Standards Journal of Research, 1929, Vol. 2, Apr., pp. 659-670). The author describes thermomagnetic analysis apparatus set up by the Bureau of Standards, and gives typical results obtained by its use.

The Magnetic Testing of Dynamo and Transformer Sheet with the Differential Iron Tester. F. Wever and H. Lange. (Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung, 1928, Vol. 10, pp. 343-362). After a review of the history of the testing of dynamo and transformer sheets, the authors describe the apparatus devised by Lonkhuyzen for determining the induction and watt loss. They then give details of tests carried out to ascertain the accuracy of the apparatus and the agreement between the results obtained with it and those obtained by other means.

Investigations of Tungsten Magnet Steel. K. G. Brecht, R. Scherer, and H. Hanemann. (Stahl und Eisen, 1929, Vol. 49, Jan. 10, pp. 41-42). The composition of the magnet steel examined was: carbon 0.67, silicon 0.26, manganese 0.25, phosphorus 0.01, sulphur 0.011, chromium 0.40, tungsten 6.62 per cent. The experiments were made to ascertain the relation between the magnetic and mechanical properties and the microstructure, as affected by various heat treatments. Specimens were annealed at various temperatures before hardening, in order to facilitate machining, and were afterwards quenched from 820° C. in water. The coercive force fell as the temperature of the previous annealing was increased, being at a minimum when the annealing temperature was 750° C., but rising again when the annealing temperature was increased to 800°. This was due to the fact that at the higher temperature some of the cementite had gone into solution, and the greater the amount of cementite that goes into solution before hardening the better the magnetic properties. If the steels are annealed at temperatures between 650° and 750°, they should be held afterwards for some time at the quenching temperature in order to allow time for the carbide to go into solution.

Investigations of Molybdenum Steels, as to their Suitability for Permanent Magnets. A. F. Stogoff and W. S. Messkin. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Mar., pp. 595-600; Stahl und Eisen, 1929, Vol. 49, Mar. 28, pp. 429-430). The magnetic properties of molybdenum steels with varying percentages of molybdenum and carbon were investigated. The steels were melted in crucibles. When the carbon is about 1.5 per cent., a molybdenum content of 2 to 2.5 per cent. is injurious, both as regards magnetic properties and in producing brittleness and spoiling the machinability. The most favourable composition for a molybdenum magnet steel is carbon about 0.9 to 1.0, and molybdenum 2 to 2.5 per cent. The magnetic properties of such a steel are considerably superior to those of ordinary tungsten

and chromium magnet steels, while the decrease in the magnetic moment due to ageing is about the same. This steel attains its best magnetic properties after quenching from 800° C. in water. It should be held at that temperature in a lead bath for 5 to 8 min. No harm is done if the above temperature is slightly exceeded. A steel with 4.33 per cent. molybdenum and 0.81 per cent. carbon quenched from 875° C. in water or oil also gives good results, but the values do not quite reach those of the first-named.

The Detection of Flaws in Rails. (Engineer, 1929, Vol. 147, May 10, pp. 522-523). The electrical device invented by E. A. Sperry for detecting transverse fissures and other flaws in rails while they lie in the track is described and illustrated.

Rail Detector Tests 2000 Miles of Track. C. W. Gennet, jun. (Paper read before the Western Society of Engineers, Mar. 4: Iron Age, 1929, Vol. 123, Mar. 7, pp. 681-682). The principle of the Sperry method of detecting flaws in rails is outlined. Its use at the rail mill and also for testing other forms of steel are suggested.

CONSTITUTION, STRUCTURE, CRYSTALLOGRAPHY.

Metallography Simplified for Practical Use in Shop. E. Preuss, G. Berndt, and M. von Schwarz. (Iron Trade Review, 1928, Vol. 83, Oct. 4, pp. 836-837; Oct. 18, pp. 991-992, 1028; Nov. 1, pp. 1116-1118; Nov. 15, pp. 1247-1249; Nov. 29, pp. 1375-1377; Dec. 13, pp. 1496-1498; Dec. 27, pp. 1624-1626; 1929, Vol. 84, Jan. 10, pp. 130-132; Jan. 24, pp. 267-269; Feb. 7, pp. 392-394; Feb. 21, pp. 520-522; Mar. 7, pp. 647-649; Mar. 21, pp. 779-781; Apr. 4, pp. 912-913, 916; Apr. 18, pp. 1054-1056; May 2, pp. 1186-1189, 1195). The continuation of a series of articles translated from the German by R. Rimbach dealing with the preparation of specimens and the investigation of the structure of metals by macroscopic and microscopic methods.

Smoothing and Etching Cupro-Nickel, Bronze, Brass, and Steel. H. B. Pulsifer. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Paper No. 137). The paper outlines a method for the rapid production of flat granular surfaces on many of the medium hard alloys. Grinding wheels and fabrics on wheels are not used; the object is accomplished by rubbing on emery-papers and on fine abrasives heaped on hard boards. The advantages of chromic acid in the solutions for etching nickel and copper alloys are explained. Steels may require an additional step in the mechanical smoothing owing to the lack of an ideal etching reagent. Chloric acid is a rapid agent

for steel. Photomicrographs are included which illustrate the steps in smoothing and the clearness with which the structures can be rapidly exposed. During the search for etching reagents most suitable for steel, an unusual structure was discovered in certain low-carbon steels (0.12 per cent. carbon). The particular pieces in question had been quenched from 1500° F. and gave a brittle crystalline fracture. Most of the stock was unquestionably ferrite, but the nature of the earlier pearlite nodules between the grains was not at first clear. When some of the sections were etched lightly with hydrochloric acid in alcohol and examined at 2000 diam. magnification, the real condition was disclosed. The heating and quenching had transformed the original pearlitic nodules into martensite and troostite. The carbon in the pearlite had failed to disseminate throughout the ferrite, and, in a miniature way, had formed the constituents of high-carbon quenched steel in a low-carbon matrix.

Microscopical Studies of a Passive Layer in Carbon Steel and the Resulting Structure. C. Benedicks and P. Sederholm. (*Zeitschrift für physikalische Chemie*, 1928, Vol. 138, Oct., pp. 123-134). In a study of etch figures produced on carbon tool steel by alcoholic nitric acid solutions, the authors noticed an unusual fissured effect which was attributed to the existence of an extremely thin passive layer; this was produced even when etch fluids containing only 0.1 per cent. of nitric acid were used. The probable origin of this film is discussed.

The Hot Acid Etch Test for Steels. F. W. Rowe. (*Iron and Steel Industry*, 1928, Vol. 2, Nov., pp. 37-40). The etching reagent prescribed for use in this test is composed of water 500 c.c., sulphuric acid 200 c.c., and hydrochloric acid 1400 c.c. The specimen, one surface of which is prepared by grinding or similar means, is immersed in the etching solution, and the temperature is raised to and held at just below boiling point for from 20 min. to 1 hr. according to the class of steel of the specimen. The author devotes considerable space to the interpretation of the structures obtained, which are illustrated. The faults revealed by the test are: (i) Pipes, (ii) seams, (iii) laps, (iv) porosity, (v) non-metallic inclusions, (vi) ingot segregates, and (vii) cracks.

New Etching Agent for Iron and Steel. V. N. Svechnikoff. (*Journal of the Russian Metallurgical Society*, 1928, No. III. pp. 105-106). (In Russian.)

The Constitution of Steel and Cast Iron—Section II. F. T. Sisco. (*Transactions of the American Society for Steel Treating*, 1929, Vol. 15). The hardening of steel is described in Part VI. (Jan., pp. 158-169). In Part VII. (Mar., pp. 503-515) the author describes and illustrates

the structure of the three transition constituents in heat-treated steel, martensite, troostite, and sorbite.

Models for the Demonstration of the Heterogeneous Equilibria in Ternary Systems. R. Vogel. (*Archiv für das Eisenhüttenwesen*, 1928, Vol. 2, Dec., pp. 389-394). The interpretation of space diagrams as usually drawn presents difficulties. The author has devised a series of models made from a transparent substance, on which the space conditions of ternary systems can be directly demonstrated.

Notes on the Iron-Silicon, Iron-Chromium, and Iron-Phosphorus Systems. P. Oberhoffer and C. Kreutzer. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Jan., pp. 449-456). The influence of silicon and of chromium on the A_3 and A_4 points in pure iron was investigated. Alloys with a content up to 2.2 per cent. silicon pass through the γ range on heating. With silicon from 2.2 to 2.5 per cent. they do not pass through the γ range on transition to the δ modification, but through a phase in which α - and γ -iron coexist. All alloys with over 2.5 per cent. silicon pass direct from the α to the δ state. Contrary to the ideas of previous investigators, it was assumed that an addition of chromium would cause a drop in the A_3 curve, followed by a rise, and that the rising A_3 point, together with the falling A_4 point, would form a contracted γ range. Thermal investigations confirmed this view, and the boundary of this contracted γ range in the iron-chromium diagram was experimentally determined at 15 per cent. chromium. An X-ray examination of the iron-phosphorus system confirmed the existence of the following compounds: at 1.7 per cent. phosphorus, saturated mixed crystals; at 15.58 per cent. the chemical compound Fe_3P ; at 21.5 per cent. the compound Fe_2P ; and above 21.5 per cent. another, hitherto unknown, iron-phosphorus compound appeared to have formed.

Iron-Manganese Alloys. V. N. Krivobok. (*Iron and Coal Trades Review*, 1928, Vol. 117, Dec. 7, p. 830). This report was presented at a recent meeting of the Metallurgical Advisory Board to the Carnegie Institute of Technology and the United States Bureau of Mines, and deals with the preparation and constitution of iron-manganese alloys and the determination of specific properties and microscopic studies.

Thermal Expansion of Iron Alloys. A. Schulze. (*Zeitschrift für technische Physik*, 1928, No. 9, Sept., pp. 338-343). Data are presented on the thermal expansion of iron-silicon, iron-aluminium, and iron-manganese alloys.

Constitutional Diagrams for Cast Irons and Quenched Steels. A. L. Norbury. (Paper read before the Iron and Steel Institute, May 1929: this Journal, p. 443).

Contribution to the Study of the Ternary Chrome Steels. J. Pomey and P. Voulet. (Paper read before the Eighth Congress on Industrial Chemistry, Strasbourg, 1928: *abstract*, *Revue de Métallurgie*, *Mémoires*, 1928, Vol. 25, Dec., pp. 665-667). A study of the transformations in chrome steels, particularly those with cobalt and nickel, at the limit of the γ range (A_4). The Fe-Cr-Co and Fe-Cr-Ni diagrams are dissected into a number of regions, and the special elements are divided into four classes according to the character of the γ range: (i) Isomorphic with α -iron (chromium); (ii) isomorphic with γ -iron; (iii) miscibility gap, but continuity of the α and δ solid solutions; (iv) miscibility gap without continuity between α -iron and δ -iron.

Abnormal Forms of Structure in Cast Steel. E. Piwowarsky. (*Stahl und Eisen*, 1928, Vol. 48, Nov. 29, pp. 1665-1669). It has often been noted that, in making experimental melts of cast steel, after annealing and recrystallisation the structure does not show the expected homogeneity. For example, a steel sample with about 0.3 per cent. carbon, deoxidised with aluminium, after annealing, continually showed a tendency for the ferrite to separate in the form of needles, and for the formation of single grains of pearlite of irregular size. Micrographs of a rail billet show a number of light spots in the fracture of a specimen subjected to static tensile test, though such spots are not present in the fractured surface of the specimen when dynamically tested. This same material also showed the peculiar phenomenon, that on recrystallisation the pearlite always had a tendency to assume the form of a network. Deep etching with concentrated sulphuric acid revealed local heterogeneity. The steel had been top-poured and aluminium had been added to each ingot shortly before the end of teeming, the weight of ingot being about $2\frac{1}{2}$ tons. A number of micrographs are given, of deoxidised and non-deoxidised steels, showing a tendency to the dendritic formation of pearlite, and these abnormalities require a good deal of further investigation in order to find a satisfactory explanation.

Pure Iron and Allotropic Transformations. T. D. Yensen. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Paper No. 185). The evolution of the iron-carbon diagram is discussed, and the question of solid solubility is briefly considered. While conclusive evidence of the absence of allotropy in pure iron in the form of heating and cooling curves and X-ray data does not yet exist, the indirect evidence obtained from iron-silicon-carbon diagrams and presented in the paper has led the author to formulate the hypothesis that pure iron has no allotropic transformations below the melting point, and that its characteristic lattice structure is the body-centred cube (α modification). It follows as a necessary corollary to this hypothesis that the A_3 and A_4 transformations are caused by carbon and other "stranger" atoms entering the interstitial spaces

of the lattice. When their amount exceeds the solubility in α -iron for the particular temperature, they cause the iron to modify its structure in order to accommodate them.

The Gamma-Alpha Transformation in Pure Iron. A. Sauveur and C. H. Chou. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Paper No. 169). Polished samples of electrolytic iron were heated to 1000° C. in a vacuum, maintained in the γ range for several hours and quenched in different media. It is shown by means of photomicrographs that the α phase forms first along the crystallographic planes of the austenite and around the grain boundaries. The martensitic structure resulting from drastic quenching is proved to penetrate to a substantial depth. There seems to be little doubt that the martensitic and the Widmanstätten types of structure are closely related.

The Transformation of Austenite into Martensite in a 0.8 per Cent. Carbon Steel. D. Lewis. (Paper read before the Iron and Steel Institute, May 1929 : this Journal, p. 427).

Further Observations on the Microstructure of Martensite. F. F. Lucas. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Feb., pp. 339-367). The author describes a number of quenching and tempering experiments in which commercial high-quality tool steels were used. Representative structures found in the quenched and various tempered conditions are discussed and illustrated by means of photomicrographs at high magnifications.

The Microstructure of Rapidly Cooled Steel. J. M. Robertson. (Paper read before the Iron and Steel Institute, May 1929 : this Journal, p. 391).

The Mode of Formation of Neumann Bands. S. W. J. Smith, A. A. Dee, and J. Young. (Proceedings of the Royal Society, 1928, [A], Vol. 121, pp. 477-514). In Part I. (pp. 477-486) the mechanism of twinning in the body-centred cubic lattice is discussed, in Part II. (pp. 486-500) evidence is put forward to show that the bands are twins, and in Part III. (pp. 501-514) the movement from which the twinning results is considered.

The Neumann Bands in Ferrite. C. H. Mathewson and G. H. Edmunds. (American Institute of Mining and Metallurgical Engineers, 1928, Technical Paper No. 139). The authors review previous work on the nature and origin of Neumann bands in ferrite, briefly discuss the characteristic features of twinning in the body-centred cubic lattice, and describe in detail the pioneer work of Mücke. Finally, the results of an X-ray investigation are introduced to prove that the

inner structure of the bands is precisely the structure required to produce the form of twinning under consideration.

Characteristic Band in Steel. V. P. Kravz-Tarnavsky. (Journal of the Russian Metallurgical Society, 1928, No. III., pp. 162-167). (In Russian.)

Banded Structure and Fracture of Steel. A. Earfurin. (Journal of the Russian Metallurgical Society, 1928, No. I., pp. 91-128). (In Russian.)

Studies in Metal Crystal Orientation. I.—Determination of Orientation of Metallic Single-Crystal Specimens by High-Voltage X-Rays. T. A. Wilson. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 210). A method is described by which it is possible to find rapidly the orientation of single-crystal specimens from which only Laue photographs can be obtained. These Laue photographs are obtained with high-voltage X-rays. The photographs are solved either by the application of the gnomonic projection alone or by the application of the stereographic-gnomonic double net.

A Metallographic Study of Tungsten Carbide Alloys. J. L. Gregg and C. W. Küttner. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 184). Five different commercial tungsten carbide alloys were investigated by means of X-ray diffraction patterns and microscopic examination. Both W_2C and WC were found in four alloys and only WC in the fifth alloy. The behaviour of two selective etching reagents is described: alkaline ferricyanide attacks WC and not W_2C ; a mixture of concentrated nitric and hydrofluoric acids attacks W_2C and not WC. The structure of the alloys containing both W_2C and WC resembles that of a eutectoid surrounded by a network of WC or a complex network.

HEAT-RESISTANT AND ACID-RESISTANT ALLOYS.

Acid-Resistant Cast Iron. F. Espenhahn. (Foundry Trade Journal, 1929, Vol. 40, Mar. 7, p. 186). An abridged English translation of a report which appeared in Die Giesserei, 1928, Vol. 15, Sept. 14, pp. 917-921. (See Journ. I. and S.I., 1928, No. II. p. 387.)

Study of a 20 per Cent. Chrome Steel. A. Michel and P. Bénazet. (Paper read before the Eighth Congress on Industrial Chemistry, Strasburg, 1928: *abstract*, *Révue de Métallurgie*, *Mémoires*, 1928, Vol. 25, Dec., p. 668).

High-Chromium Steels. O. K. Parmitter. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, May, pp. 796-813). The author discusses in general the composition, heat treatment, and properties of high-chromium steels, including the various low-carbon, stainless steel types, and the several high-carbon chromium die types. Special consideration is given to the more recent development of stainless steel containing nickel and chromium. The effect of various chemicals and other corrosive substances upon stainless steel is dealt with in detail.

Iron-Chromium-Nickel Alloys. (Metallurgist, 1929, Vol. 5, Feb., pp. 30-31). A critical review of Guertler's paper on the relation of the space lattice of alloys and their corrosion resistance (*Zeitschrift für anorganische Chemie*, 1919, Vol. 107, p. 1), and of his later paper containing the results of experiments made to determine if there were any relation between that theory and the practical results of tests on the acid resistance of iron-chromium-nickel alloys (*see* Journ. I. and S.I., 1928, No. II. p. 434).

Rust-, Acid-, and Heat-Resisting Steels. (Iron and Steel of Canada, 1928, Vol. 11, Dec., pp. 377-379).

Heat- and Corrosion-Resistant Alloys. T. H. Nelson. (Iron Age, 1929, Vol. 123, Apr. 25, pp. 1139-1142). The analyses and properties of the three chief types of stainless steel are discussed.

A New Development in Corrosion-Resisting Steel. F. R. Palmer. (Transactions of the American Society for Steel Treating, 1928, Vol. 14, Dec., pp. 877-892, 950). It was found that 0.40 per cent. of zirconium sulphide added to a high-chromium stainless iron greatly improved the machining and grinding properties, and served to reduce the tendency toward galling, scratching, and seizing. This was accomplished by a slight loss of toughness and tensile properties, but yielded a metal which was eminently suited for many corrosion-resisting parts. Zirconium sulphide tended to prevent air-hardening in the low-carbon grades of stainless iron and raised the temperature necessary for hardening.

Some Applications of Stainless Steel. (Metallurgist, 1928, Vol. 4, Dec. 28, pp. 190-191). A three-cylinder pump, built for a pressure of 10,000 lb. per sq. in., was fitted with one stainless steel piston and two of phosphor-bronze. On examination after running day and night for about 3 years the stainless steel piston was found to have been reduced only 0.4 mm. in diam., while the other two pistons were 2.8 mm. smaller. The behaviour of stainless steel when used for turbine blades is also dealt with. In one turbine, stainless steel blades and

5 per cent. nickel steel blades were fitted and compared after running; in another case stainless steel—hardened, and hardened and tempered—phosphor-bronze, nickel-bronze, soft steel, and brass blades were tested together. In both tests the stainless steel demonstrated its superior properties and ability to resist erosion.

Stainless Iron and its Application to the Manufacture and Transportation of Nitric Acid. W. M. Mitchell. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Feb., pp. 303-338). A brief account is given of the recently developed ammonia oxidation process for the manufacture of nitric acid. The resistance of various materials to nitric acid, and the superiority of the high-chromium alloys for this purpose, are discussed. The requirements are set forth for suitable materials for the construction of equipment for the manufacture and transportation of nitric acid. Existing specifications for stainless iron for this purpose are critically examined, and specifications for plates, rivets, tubing, castings, tank cars, and shipping drums are considered in detail.

Effect of Temperature on Stainless Iron. R. Sergeson. (Heat Treating and Forging, 1929, Vol. 15, Jan., pp. 55-59). The paper contains the results of an investigation of "Enduro 18-8," a stainless iron made by the Central Alloy Steel Corporation, of the following composition: carbon under 0.12, manganese under 0.50, sulphur under 0.03, phosphorus under 0.03, silicon under 0.50, chromium 17 to 19, and nickel 8 to 9 per cent. The physical properties after various heat treatments are recorded, and micrographs of the structure are reproduced. In the hot-rolled and austenitic state the metal is not improved by heat treatment, as its strength is dependent on the composition only. Cold-work increases the tensile strength and hardness, markedly at first and then more gradually; the elongation, reduction of area, and impact values suffer corresponding decreases. On reheating cold-worked bars to 1200° F. (650° C.) most of the increased strength due to the cold-work is lost. To restore completely the structure and impact value of cold-worked material, it must be heated to 1850° F. (1010° C.); above that temperature grain-growth occurs, though not markedly until 2200° F. (1205° C.) is reached. To obtain a fully austenitic structure the metal is quenched from 2100° F. (1150° C.) in water, oil, or air according to the section. Short-time tensile and impact tests at elevated temperatures, comparing hot-rolled bars reheated to 1200° F. with cold-drawn bars reheated to the same temperature, were favourable to the former, particularly the impact tests. Hot-rolled bars annealed at 1900° F. (1040° C.), when impact tested at elevated temperatures, showed excellent toughness without any blue brittleness. Creep tests between 1000° F. (540° C.) and 1200° F. are recorded. It is recommended that this alloy should not be used above 1800° F. (980° C.) for continuous service.

Chromium-Copper Steels as Possible Corrosion-Resisting Ferrous Alloys. B. D. Saklatwalla and A. W. Demmler. (Transactions of the American Society for Steel Treating, 1929, Vol. 15, Jan., pp. 36-48). The authors present a study of the physical and corrosion-resisting properties of chromium-copper steels.

The Scope of Corrosion-Resisting Steels in Chemical Engineering. T. H. Burnham. (Industrial Chemist, 1928, Vol. 4, Aug., pp. 320-324).

Corrosion-Resistant Metals and Alloys. (Chemical Age, 1928, Vol. 19, Aug. 25, pp. 157-158).

Heat-Resisting Alloys and Their Use in Steel Plant. J. D. Corfield. (Iron and Steel Engineer, 1929, Vol. 6, Apr., pp. 157-164). The author outlines the properties of heat-resisting alloys, and points out a number of uses for them in iron and steel plants.

Chromium Alloys. F. M. Beckett. (Address presented to the Institute of Metals Division of the American Institute of Mining and Metallurgical Engineers, 1928). The author discusses the early development and recent applications of chromium alloys under the following headings: Early researches in Britain, early manufacture, chrome steel armour plate, compound chromium steels, manufacture in electric furnaces, classification of chromium steel, effect of heat treatment, effect on critical points, chromium in cast iron, discovery of stainless steel, rustless iron, minimum corrosion, application of rustless iron, value at high temperature, applications of chrome-iron, addition of nickel, resistance to oxidation, application of high-chromium nickel steels, and chromium plating.

CORROSION OF METALS.

(For Coating of Metals, see p. 760.)

The Erosion of Guns. R. H. Greaves, H. H. Abram, and S. H. Rees. (Paper read before the Iron and Steel Institute, May 1929: this Journal, p. 113).

Laboratory Corrosion Tests of Mild Steel, with Special Reference to Ship Plate. H. S. Rawdon. (Bureau of Standards Journal of Research, 1929, Vol. 2, Feb., pp. 431-440). In 1919 a number of steel plates of English manufacture were fitted into the hull of s.s. *Leviathan*, and a subsequent examination showed that the original German plates had resisted the corrosion of sea-water much better than the English plates. Samples of both steels were tested by G. B. Waterhouse

(Iron Trade Review, 1924, Vol. 75, July 24, pp. 229-230), who was unable to assign a definite reason for the difference in corrosion behaviour of the two types of steel. Possible reasons, which he suggested, for the superiority of the German plate were the presence of a comparatively high percentage of copper and a marked banded structure, whereby after moderate corrosion low-carbon layers would be exposed to the sea-water. The English steel was stated to have the appearance of ordinary acid open-hearth steel with no marked characteristics to distinguish it from ordinary plate, except that copper was present in moderate amount. The copper contents of the two steels given by Waterhouse were 0.169 per cent. for the original *Leviathan* plate and 0.134 per cent. for the plate of English manufacture. In order to determine whether or not the differences in corrosion resistance cited above and in other cases can be demonstrated in the laboratory, a series of corrosion tests of mild steel, including some *Leviathan* and other ship plates, was made by the wet-and-dry method and the continuous immersion methods in salt-water solutions, and the results are presented by Rawdon. The steels varied in copper content from a trace to over 0.60 per cent. No differences in corrosion rate indicating marked superior corrosion resistance of any of the compositions used were obtained. The differences in corrosion behaviour observed were those resulting from differences in the test methods employed. The corrosion rate in the wet-and-dry test decreased as the surface film was built up, but was always much higher than that for simple immersion. The laboratory test results have not confirmed in any way whatsoever the claims made for the *Leviathan* plate for unusually superior corrosion resistance. It is believed that differences in the service conditions, the importance of which has apparently not been fully appreciated, will account satisfactorily for the alleged difference in the corrosion behaviour of these steels.

The Preliminary Treatment of Iron Electrodes for Corrosion Experiments. W. van W. Scholten. (Korrosion und Metallschutz, 1928, Vol. 4, Dec., pp. 265-272). The author gives many references to the work of other investigators bearing on the effects caused by the preliminary preparation of test-pieces for corrosion tests, and records his own experiments made to determine the nature and extent of the effects. Such matters as the effect of rubbing the specimens with emery-paper, washing them with alcohol, allowing them to remain in the air for various periods before subjecting them to the test, &c., were investigated. (See also p. 820.)

Observations Concerning Corrosion Tests. J. M. Pouvreau. (Aciers Spéciaux, 1929, Vol. 4, Jan., pp. 23-24). The author points out the necessity for the standardisation of the conditions employed in making corrosion tests, and for reporting full details concerning both the corrosive agents and the test specimens employed.

Corrosion of Iron. W. van W. Scholten. (Gas- und Wasserfach, 1928, Vol. 71, Sept. 8, pp. 872-880).

Is the Problem of Corrosion Solved? A. Matagrín. (Röhren-industrie, 1929, Vol. 22, Mar. 14, pp. 86-87; Apr. 11, p. 120). A review of the work and opinions of other investigators.

The Mechanism of Corrosion. U. R. Evans. (Journal of the Chemical Society, 1929, pp. 111-129). The manner of the corrosion of half-immersed specimens, the rate at which it spreads in various solutions, and the different types of corrosion products formed are discussed. Quantitative experiments to determine the rates of attack of different specimens (iron, steel, zinc, aluminium, copper) in different solutions are recorded, and the reasons for the differences observed are explained.

The Electrical Behaviour of Surfaces of Corroding Iron. A. L. McAulay and S. H. Bastow. (Journal of the Chemical Society, 1929, pp. 85-92). The investigation was planned to elucidate the mechanism giving rise to corrosion currents; part of the work was concerned with the attainment and recognition of a standard condition for metal and solution. It was found that a piece of iron placed in an air-free electrolyte tends towards a stable potential, which is probably determined ultimately by the hydrogen-ion concentration of the solution; the condition is slowly attained and is reproducible. The behaviour of pure iron was typical of that of mild steel and cast iron; the composition had little effect provided that it did not produce air passivity, as in stainless steel.

On the "Colloid Theory" of the Process of Rusting. G. Schikorr. (Korrosion und Metallschutz, 1928, Vol. 4, Nov., pp. 242-245). The author recounts briefly Newton Friend's colloidal theory of the mechanism of rusting, and discusses it critically, giving references to the work of other investigators. He maintains that the main argument of Friend's theory—similarity between the action of electrolytes on the coagulation of the Fe_2O_3 -sol and the corrosion of iron—is not valid; in the range of lower concentrations, where the differences in the coagulating action of electrolytes is most marked, there is no corresponding agreement in the rusting process. A basic assumption—oxidation of the FeO -sol to Fe_2O_3 -sol—is at variance with experiment; under the action of air the FeO -sol is flocculated as a higher oxide. The fact that led to the formulation of the theory—maximum corrosion for medium speeds of flow of the water—is explained equally well by the old theory. That the speed of rusting increases to a maximum value in the neighbourhood of 1 atm. as the oxygen pressure rises is satisfactorily explained by the old theory, but is entirely missed by the colloidal theory.

On Retardation and Prevention of Oxidation. J. G. A. Rhodin. (Engineer, 1929, Vol. 147, Jan. 18, pp. 66-68; Jan. 25, pp. 92-93). The author outlines the contents of a recent paper by C. Moureau and C. Dufraisse on "The Negative Catalysis of Auto-Oxidation or Anti-Oxygenic Activity" (Chemistry and Industry, 1928, Vol. 47, Aug. 10, pp. 819-828; Aug. 17, pp. 848-854). The French investigators carried out experiments in which the tendency of various easily oxidised substances to combine with oxygen was reduced or nullified by the addition of a third substance in very small proportion. The author of the present article then applies the Frenchmen's ideas to the problem of the corrosion of iron and steel, and suggests experiments which could be carried out in a modified form of their apparatus.

The Passivity of Metals. Part II.—The Breakdown of the Protective Film and the Origin of Corrosion Currents. U. R. Evans. (Journal of the Chemical Society, 1929, pp. 92-110). From the experimental results recorded in the present paper (for Part I. *see* Journ. I. and S.I., 1927, No. II. p. 642), the author concludes that the breakdown of the protective film on iron, steel, zinc, or aluminium tends to occur where the surface has been bent or cut, or where rolling or casting defects occur at the surface; at these points local corrosion sets in, and usually spreads, although dissolved oxygen in excess may heal up the weak point. Pre-existing cavities may be the sites of corrosion, as in zinc, their interiors being inaccessible to repairing oxygen; but this cannot be a common cause of localised attack, which can be obtained under anaerobic conditions if an external e.m.f. be applied. Internal stresses are important in determining corrosion if they are such as to keep the film in a state of weakness. "Differential aeration currents" are due to the differences of potential existing between places where the film is kept in repair by oxygen and those where it is not repaired; e.m.f.'s approaching 0.5 v. due to this cause were measured, but they fell off when a current actually flowed. The extension of breakdown, or the repair of the film, could be followed by potential changes.

The Passivity of Metals and its Relation to Problems of Corrosion. U. R. Evans. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Paper No. 205).

Corrosion—Note on an Apparent Relation of Protective Film to Microstructure. C. Van Brunt. (Industrial and Engineering Chemistry, 1929, Vol. 21, Apr., p. 352). The author discusses the corrosion of a gear pump used to force a sodium xanthate solution of cellulose into the spinnerets of a rayon mill. With certain exceptions, all parts of the apparatus coming into contact with the solution showed a thin but dense and adherent coating of ferrous sulphide, which constituted an efficient protective film against progressive corrosion. The corrosion of the gear-teeth was heaviest at the point of greatest movement

between parts, indicating that the film had been sheared or rubbed off. It is believed that the segregation of impurities along grain boundaries characteristic of cast iron was in some way primarily responsible for the destruction of the protective film, probably by causing coincident lines of weakness in the film, and thus facilitating mechanical disruption. On this hypothesis segregation along grain boundaries may play a vital part in the resistance of alloys in general to combined corrosive and mechanical attack, and may account for the effect of relatively minute percentages of components. The effect may be constructive quite as easily as destructive, since the segregated matter can be thought of as forming a resistant as well as a non-resistant deposit against chemical attack.

Some Examples of the Corrosion of Metals. C. O. Bannister. (Paper read before the Society of Chemical Industry, Nov. 1928 : Iron and Coal Trades Review, 1928, Vol. 117, Nov. 23, p. 768). The author presents the results of investigations of some examples of corrosion, including galvanised sheets and cast-iron pipes.

Corrosion of Metals as Affected by Stress, Time, and Number of Cycles. D. J. McAdam, jun. (American Institute of Mining and Metallurgical Engineers, 1929, Technical Publication No. 175). This paper discusses the interrelationship of stress, time, and number of cycles in causing penetration of metals under corrosion. The resultant fatigue limit is used as a criterion of the depth and sharpness of corrosion pitting. Four variables and their interrelationship therefore are considered.

The paper first discusses the relationship between corrosion stress and resultant fatigue limit with the other two variables held constant. The form of the graph representing this relationship indicates local strengthening of the metal at the bottoms of the corrosion pits. The field of investigation was then extended to include stresses between zero and the endurance limit. By thus widening the range of corrosion stresses it was then possible to extend the range of cycle frequencies so as to include frequencies as low as 5 cycles per hour. "Constant-damage" graphs were then developed so as to represent the stress-time-cycle relationship with resultant fatigue limit held constant. Constant-damage series of graphs are discussed as various sections of constant-damage surfaces. Constant-damage graphs and surfaces on a logarithmic scale are found to be the most useful method of representing the relationship between the four variables. Graphs for alloy steels varying widely in composition and physical properties are discussed. From the constant-damage graphs, other graphs and surfaces are developed to represent the damage (due to cyclic stress) in excess of the amount of damage that would be caused by stressless corrosion alone. The effect of steady and intermittent tensile stress on corrosion, the stress-time-cycle relationship as affected by varying

corrosion conditions, and the stress-time-cycle relation as it affects the corrosion of corrosion-resistant steels and non-ferrous metals are also discussed.

Corrosion Fatigue of Metals. (Metallurgist, 1929, Vol. 5, Jan., pp. 3-6; Mar., pp. 44-48). These articles are based on six papers published by D. J. McAdam relating to research on corrosion fatigue carried out at the Experiment Station of the U.S. Navy at Annapolis. The first article summarises the general characteristics of corrosion fatigue, as described by McAdam in his first four papers, while the second article relates to his latest paper dealing with the isolation of the effects of individual factors (*see* Journ. I. and S.I., 1928, No. II. p. 403).

The Effect of Cold-Working on the Corrosion of Iron and Steel. H. Endo. (Science Reports of the Tôhoku Imperial University, Sendai, 1928, Vol. 17, pp. 1265-1278). The weight loss of steel of various carbon contents, which were subjected to different kinds of mechanical stress, was examined by immersing the sample in a 1 per cent. sulphuric acid solution, kept at 25° C., for 72 hr. In the case of a tension applied up to breaking point, the weight loss runs exactly parallel to the amount of deformation. In the portion of the specimen where the stress is the greatest, the maximum weight loss is obtained with a 0.9 per cent. carbon steel. In the case where a certain amount of torsion was applied the weight loss also increased with the amount of torsion, the maximum loss being also obtained with the 0.9 per cent. carbon steel. Generally, the heaviest attack from the acid occurs at the point where the twist is greatest. In the case of compression the weight loss also increases with the load, although the corresponding maximum loss could not be obtained at the 0.9 per cent. carbon content. The effect on the corrosion of such a small amount of repeated impact as to cause no permanent deformation is not appreciable.

The Corrosion and Rusting of Plain and Alloyed Cast Iron. P. Kötzsche and E. Piwowarsky. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Nov., pp. 333-340). An investigation was made to discover the influence on the corrodibility of cast iron of the form and quantity of graphite, of the silicon, of nickel and chromium separately and together, and of copper. It was found that the mode of graphite separation, on overheating or at different cooling rates, exercised no appreciable influence on the corrodibility of cast iron in acids or in salt solutions. The quantity of graphite per unit of surface likewise did not affect the corrodibility. Silicon should be kept as low as possible (below 1.5 per cent.) for grey cast iron to have the best resistance to corrosion by acids and alkaline solutions. Nickel additions up to 6 per cent. have little influence in preventing corrosion of grey cast iron in the presence of acids and salt solutions. Chromium up to 1 per cent. has a marked influence in regard to corrosion by acids, but

at the expense of machinability ; against salt solutions it is without influence. Chromium and nickel together (Cr 0.5, and Ni 2.5 per cent.) greatly reduce the attack by acids, but with salt solutions rather the reverse is the case. An addition of 0.3 to 0.4 per cent. of copper increases the resistance of grey cast iron to weather by 25 per cent., but up to 0.9 per cent. copper the resistance to acid attack is unaltered, and the resistance to salt solutions is reduced.

The Surface Treatment, Deoxidation, and Corrosion of Boiler Tubes, Water and Steam Pipes. B. Schulz. (*Wärme*, 1927, Vol. 50, Oct. 17, pp. 689-694).

Investigation on the Corrosion of a Galvanised Iron Hot-Water Cylinder. H. F. Richards. (*Iron and Steel Industry*, 1928, Vol. 2, Nov., pp. 45-46). The failure of a galvanised hot-water tank by perforation of the bottom was investigated. Analyses of the water and the corrosion products are recorded, from which it was concluded that the presence in the water of carbon dioxide, and also of chlorides and nitrates, was the primary cause of the trouble. The mechanism of the corrosion process is explained : such water will attack zinc ; after a while the crystals of the iron-zinc compound lying between the iron base and the zinc coating are laid bare ; and, owing to the difference between the electrode potential of the zinc and of the crystals, the corrosion will become intensely localised, causing pitting and, finally, perforation.

Relations between the Corrosion of Superheaters and the Incrustation of Turbine Blades. C. Roszak and M. Pillet. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Nov., pp. 647-651).

Corrosion in Centrifugal Pumps. R. W. Müller. (*Korrosion und Metallschutz*, 1929, Vol. 5, Mar., pp. 59-61). The author gives examples of corrosion in centrifugal pumps and discusses the causes of the troubles which occur.

On the Resistance of Some Steels Towards Chemical Influences in Relation to the Carbon, Nickel, and Chromium Contents. F. Schmitz. (*Zeitschrift für Metallkunde*, 1929, Vol. 21, Feb., pp. 64-65). The resistance to chemical action of three series of steels was investigated : (1) unalloyed steels with rising carbon contents ; (2) steels containing 8 to 18 per cent. of chromium and a rising nickel content of from 0.5 to 62 per cent. ; (3) steels with high chromium and very high carbon contents, but with relatively little nickel. Polished specimens, $20 \times 20 \times 10$ mm. with a 4-mm. hole bored in them, were suspended for 180 hr. in liquids the action of which was to be investigated ; the temperature was 18° C. The liquids included tap-water, artificial

sea-water (in this medium tests were also continued for 900 hr.), and various strengths of mineral and organic acids, ammonia, and potash. Scaling tests, in which $20 \times 20 \times 100$ -mm. specimens were placed for 180 hr. in the oxidising gases from a hardening furnace at 850° to 900° C., were also made. The analyses of the materials and the results obtained are set out in two tables. The scaling tests demonstrated the increasing protection afforded by a rising carbon content. The author's conclusions parallel closely those of Guertler and Ackermann (*Zeitschrift für Metallkunde*, 1928, Vol. 20, pp. 269-270). Under oxidising conditions chromium is the only protective agent; under non-oxidising conditions nickel is the constituent which exerts a beneficial action on the steel.

Testing Processes for the Determination of the Corrosion Resistance of Metals to Weather and Sea-Water. E. Rackwitz and E. K. O. Schmidt. (*Korrosion und Metallschutz*, 1929, Vol. 5, Jan., pp. 7-13). The article constitutes Report No. 127 of the Deutsche Versuchsanstalt für Luftfahrt, E.V., Berlin-Adlershof. Methods and apparatus employed in making various types of corrosion tests are described and illustrated. The results described, however, refer to experiments carried out on light-metal alloys.

Effect of Additions of Lime and Soda-Ash to Brackish Water on the Corrosion of Iron and Steel. H. O. Forrest, J. K. Roberts, and B. E. Roetheli. (*Industrial and Engineering Chemistry*, 1929, Vol. 21, Jan., pp. 33-35). The treatment of brackish or semi-salt water to retard the corrosion of exposed iron or steel structures has been studied. Additions of lime to waters high in bicarbonate and calcium content will cause the formation of protective calcium carbonate scales. Waters containing appreciable quantities of magnesium salts require soda-ash as well as lime treatment to increase the *pH value* and supply carbonate ions before a calcium carbonate scale can be built up. An *pH value* of 8.5 or higher is favourable to the formation of protective carbonate scales. For practical application larger scale studies are recommended to determine the minimum quantity of lime or soda-ash necessary to maintain a thin protective scale on the structure.

Corrosion of Iron in a Sodium Chloride Solution. W. van W. Scholten. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Feb., pp. 523-530). The author has studied the influence of the character of the surfaces and contact with oxygen on the solubility of iron electrodes. The tests were made in a sodium chloride solution with occasional stirring for short and long periods. One of the iron electrodes had a roughened surface, while the surface of the other was polished. The simple measurement of the voltage at the terminal showed that on stirring the liquid a change in the polarity of the electrodes took place. By means of measurements at both electrodes an explanation of this

change of polarity was found, and the nature of the surfaces has much to do with it. (*See also* p. 814.)

Speech of Welcome at the Annual Meeting of the Reichsausschuss für Metallschutz [Imperial Committee for Metal Protection] and Report on the Scientific Work of the Committee during the Last Year. E. Maass. (*Korrosion und Metallschutz*, 1929, Vol. 5, Jan., pp. 1-7). The speech forms an interim report on work done by the author and his collaborator, Dr. Wiederholt, on "The Resistance of Metallic Alloys to the Action of Salts and Salt Solutions," such as occur in the alkali industry.

The Solution Velocity of Iron. W. Schreck. (*Giesserei Zeitung*, 1928, Vol. 25, Dec. 1, pp. 674-679). Experimental determinations of the velocity of solution of cast iron in acids are recorded. Graphite increases the rate of solution, and various suggestions made by other workers for reducing the graphite content are discussed.

The Corrosion of Steel by Acid Solutions. H. Endo. (*Science Reports of the Tôhoku Imperial University, Sendai*, 1928, Vol. 17, pp. 1245-1263). This paper contains the results of experiments on the corrosion of steels when immersed in hydrochloric, sulphuric, and nitric acid solutions—the steels containing various amounts of carbon, cobalt, nickel, chromium, manganese, molybdenum, vanadium, tungsten, copper, titanium, phosphorus, silicon, and sulphur. The relation between the solution of hardened steels in a sulphuric acid solution and the degree of tempering has also been studied.

Organic Type Inhibitors in the Acid Corrosion of Iron. J. C. Warner. (Paper read before the American Electrochemical Society, May 1929). Further evidence is presented which substantiates the theory that inhibitors of the organic type function by increasing the over voltage required for the deposition of hydrogen. The effect of various concentrations of gelatine upon the energy required for the deposition of hydrogen on iron was studied, and the results are compared with the inhibitor action of gelatine in the acid corrosion of iron. The effect of small quantities of quinoline, aniline, bases from petroleum fractions, and bases from coal-tar oils, upon the energy required for the deposition of hydrogen was also studied, and the effectiveness of these substances as inhibitors in the acid corrosion of iron was determined. The experiments indicate that any substance which will form a large positively charged oily ion, or a positively charged oily, colloiddally dispersed particle, in acid solution, should inhibit the acid corrosion of iron if the substance cannot be electrolytically reduced.

The Electrochemical Corrosion of Painted or Lacquered Steel, with Special Reference to the "Alkaline Peeling" of the Coat. U. R. Evans.

(Paper to be read before the American Electrochemical Society, May 1929). The author has made a detailed study of failures of steel sheets due to cathodically produced alkali. Five series of experiments were performed, designed to study the effect of varying (1) the varnish medium; (2) the surface condition of the steel; (3) the method of applying the varnish; (4) the salt solution; (5) the pigment, where present. When a drop of salt water rests on a steel sheet protected by an imperfect coat of varnish or paint, the sodium hydroxide, formed as the cathodic product around the edges of the drop, may produce alteration or loosening of the coat, so that it can be removed by quite gentle rubbing. The loosening may extend over an area far exceeding that originally covered by the drop, owing to the creepage of the alkali over the metallic surface. Salts which do not produce caustic alkali have comparatively little action. The peeling only occurs if there is some slight porosity or imperfection in the paint, which allows a minute amount of corrosion, but an amount of corrosion which would be harmless in its direct effect may nevertheless cause stripping over a large area. The nature of the metallic surface affects the result, while different varnishes and paints behave quite differently from one another. It is impossible to forecast the liability of a coat to "alkaline peeling" from its appearance or from the degree in which it protects the metal from corrosion; some coats of bad appearance resist peeling to a wonderful extent, while some coats of excellent appearance peel readily. Certain linseed varnishes, containing copal, are less susceptible to peeling than corresponding mixtures without copal. The introduction of certain pigments into the coat also reduces the danger of peeling, either by strengthening the coat, diminishing the permeability, or by keeping the metal passive. Thick coats are usually less susceptible than thin coats. Several observations have been made regarding the action of different pigments in arresting or stimulating corrosion, and the conclusions reached are in general accord with those of Cushman and Gardner in America, and of Ragg in Germany.

Factors Affecting the Relative Potentials of Tin and Iron. E. F. Kohman and N. H. Sanborn. (Industrial and Engineering Chemistry, 1928, Vol. 20, Dec., pp. 1373-1377). Data here given show that products similar to those found in canned fruits—namely, apple pomace, prune kernels, and other protein-bearing products markedly change the relative potentials of iron and tin in various acid solutions. In acid solutions in which tin is anodic to iron, these products render it even more anodic. In solutions in which tin is cathodic they may cause it to become anodic to iron. The single potential of tin in various acids is shown to be markedly affected by the hydrogen-ion concentration, while that of iron is little affected, if at all. The higher the hydrogen-ion concentration the less noble tin becomes. It is shown that small quantities of tin in solution have a marked effect in inhibiting iron

corrosion. In explanation of this it is shown that such quantities of tin in solution have a marked effect in raising the cathodic polarisation on iron at low current densities. Apple pomace likewise is shown to influence cathodic polarisation on iron in a similar manner. The conductivity of the electrolyte is found to be a negligible factor in influencing corrosion in canned fruits. These data are discussed in connection with viewpoints of others and shown to be in harmony with commercial experience in the corrosion resulting in canned fruits.

The Ferroxyl Indicator. W. van W. Scholten. (*Korrosion und Metallschutz*, 1929, Vol. 5, Mar., pp. 62-64). The author describes corrosion tests made with the ferroxyl indicator present in the solution. Earlier workers had added agar-agar to the solution, but the present author used the indicator without any such addition. In use, he added 1 c.c. of a 1 per cent. alcoholic solution of phenolphthalein and 2 c.c. of a 1 per cent. aqueous solution of potassium ferricyanide to 250 c.c. of the molar sodium chloride solution (58.46 gm. NaCl per litre) used as the corrosive medium. The anodic portions of the steel under test turned blue while the cathodic parts turned red. He discusses the most suitable conditions for using the indicator.

LABORATORY EQUIPMENT.

New Research Laboratory at East Chicago. (*Heat Treating and Forging*, 1929, Vol. 15, Feb., pp. 174-177). The laboratories of the American Steel Foundries are illustrated and briefly described.

CHEMICAL ANALYSIS.

ANALYSIS OF IRON AND STEEL.

Methods of Chemical Analysis in Iron and Steel Works. L. Persoz. (*Revue de Chimie Industrielle*, 1928, Vol. 37, Oct., pp. 327-329). Methods for the determination of molybdenum, titanium, copper, aluminium, uranium, and zirconium are described.

Chemical Analysis for the Small Foundry. (Iron and Steel Industry, 1929, Vol. 2, Jan., pp. 103-104). Brief notes on apparatus required, sampling, and the estimation of graphite, combined carbon, silicon, manganese, phosphorus, and sulphur, are given.

The Estimation of Carbon in Steel Wire. H. N. Marr. (Iron and Steel Industry, 1929, Vol. 2, Mar., pp. 184-185). The author records the results of experiments carried out to determine the scope and accuracy of a method for the estimation of carbon in steel wires by direct combustion in oxygen, in which millings of dead mild steel of known carbon content are used as a flux. The method is intended for use for hard wires, or wires of fine gauge, from which it is difficult to prepare millings

The Determination of Sulphur by the Evolution Process in Steels and Cast Iron. N. D. Ridsdale. (*Analyst*, 1929, Vol. 54, Mar., pp. 166-167; *Chemistry and Industry*, 1929, Vol. 48, Jan. 18, pp. 59-60). All carbon steels and cast irons when in the form of millings, drillings, &c., after being in contact with air for a long time (say, 2 years), fail to yield the full quantity of sulphur as sulphide when dissolved in hydrochloric acid. This can be remedied by annealing the metal in an oxygen-free atmosphere. A simple method for this treatment avoiding complicated apparatus is as follows: 5 gm. of drillings are mixed with 0.5 gm. of dry powdered cream-of-tartar and placed in a porcelain crucible (top diam. $1\frac{5}{8}$ in., $\frac{7}{8}$ in. high), which is then filled to the brim with a mixture of 95 per cent. of acid-washed, 40-mesh, calcined sea-sand, and 5 per cent. of powdered cream-of-tartar. On it is placed a capsule, $1\frac{3}{4}$ in. in diam. and $\frac{1}{2}$ in. deep. The whole is inverted, the outer space filled with the sand mixture, and the capsule and crucible are put slowly into a muffle at 750° to 850° C. and kept there for 20 min. When cool the entire contents are transferred to the sulphur flask and the usual sulphide evolution carried out. A blank must be run on the sand and cream-of-tartar. White irons and certain

alloy steels which do not yield their sulphur as sulphide by direct evolution may be successfully treated in this way.

A Rapid Method for Dissolving High-Chromium Steels for the Determination of Sulphur. B. S. Evans. (Analyst, 1929, Vol. 54, May, pp. 286-287). After dissolving high-chromium steel in *aqua regia* a very difficultly soluble sludge usually remains. The apparatus described and sketched by the author is intended to permit of solution in hydrochloric acid first, in order to avoid the passivity induced by the nitric acid. It consists of a 700-c.c. flask with a ground-glass stopper carrying a tapped funnel, the stem of which reaches the bottom of the flask, and a leading tube, the long arm of which reaches (outside) to the level of the flask bottom, the short arm just passing through the stopper. The sample is placed in the flask and covered with water; the leading tube end is dipped into concentrated nitric acid, and concentrated hydrochloric acid is added to the flask through the funnel. After complete solution is attained by gentle warmth, care being taken that the leading tube always dips in the nitric acid, the tap funnel is opened and the flask cooled. The funnel is closed and hot water poured over the flask; this expands the gases in the flask and bubbles the remaining sulphide gas through the nitric acid. The flask is then immediately put under the cold tap, causing the nitric acid to be sucked back into the flask; this should occur so rapidly that the vessel containing the nitric acid is emptied before the acid can react with the ferrous salts, which it does with violence. All parts of the apparatus are rinsed, and the sulphur determination carried out in the usual way.

The Electrometric Titration of Manganese by the Volhard Method. B. F. Brann and M. H. Clapp. (Journal of the American Chemical Society, 1929, Vol. 51, Jan., pp. 39-41).

The Influence of Cobalt on the Determination of Manganese in Steel. I. Wada and S. Saito. (Bulletin of the Institute of Physical and Chemical Research, Tokyo, 1928, Vol. 7, Oct., pp. 1002-1027). (In Japanese.) The authors have investigated whether the presence of cobalt interferes with the determination of manganese when it is oxidised to permanganate in nitric acid solution with sodium bismuthate and then titrated with a solution of ferrous ammonium sulphate. It was found that manganese in steel cannot be titrated by this method in the presence of cobalt.

The Determination of Manganese. W. A. Walters. (Swansea Technical College Metallurgical Society, Mar. 16, 1929). An outline is given of the bromine precipitation process and volumetric methods for determining manganese. The precautions necessary for accurate results are pointed out.

Volumetric Determination of Vanadium by Means of Potassium Iodate. E. H. Swift and R. H. Hoeppel. (Journal of the American Chemical Society, 1929, Vol. 51, May, pp. 1366-1371). A method for the volumetric determination of vanadium by means of standard solutions of potassium iodide and potassium iodate has been developed. The method depends upon the reduction of vanadate by a known amount of iodide in hydrochloric acid solution, and conversion of iodine formed and of the excess of iodide into iodine monochloride by titration with iodate. It is shown that when the concentration of the hydrochloric acid is 6 molar or more, quadrivalent vanadium is not oxidised by the iodine monochloride and the reactions are quantitative. Test analyses proved that vanadate can be determined by this method in the presence of phosphate, arsenate, or ferric iron, and also in the presence of tungstic acid, which may be held in solution by adding phosphoric acid.

Iodometric Determination of Vanadium in Special Steels and in Ferro-Vanadium. K. Roesch and W. Werz. (Zeitschrift für analytische Chemie, 1928, Vol. 73, pp. 352-355). The method is based on the reduction of V_2O_5 to V_2O_4 by KI in the presence of phosphoric acid; the I_2 liberated is titrated. For special steels, 1 grm. of sample is fused with NaOH for 10 min.; the mass is leached with boiling water, and the solution is made up to 500 c.c. 50 c.c. is pipetted out, and 75 c.c. of H_3PO_4 (density, 1.7) are added, followed by KI; the iodine liberated is titrated with $Na_2S_2O_3$ standard solution. The treatment for ferro-vanadium samples is more complicated.

Determination of Vanadium in Steel. K. Swoboda. (Chemiker-Zeitung, 1928, Vol. 52, pp. 1014-1015). 2 grm. of sample is dissolved in 50 c.c. of sulphuric acid (1:6) in a large flask; the loss of water during solution is made up. The boiling liquid is oxidised by drops of nitric acid, and an excess of 5 c.c. is added; the red fumes are expelled. Boiling is continued for some minutes after 50 c.c. of a 10 per cent. solution of ammonium persulphate have been added, and again after adding ammonia in excess. The heat is removed and 50 c.c. of ammonium persulphate and 100 c.c. of ammonium molybdate solutions are added. The precipitate is dissolved in strong nitric acid; to the clear boiling liquid 3 or 4 drops at a time of 10 per cent. sodium phosphate solution are added at intervals of 20 sec., until the colour of the precipitate changes from dark orange to yellow-orange, marking the completion of the vanadium precipitation. The liquid is boiled down to very small bulk; the precipitate is collected and washed with a solution containing 20 c.c. of ammonia (sp. gr. 0.91) and 25 c.c. of strong sulphuric acid per litre. Filter and precipitate are heated in 50 c.c. of nitric, 5 c.c. of phosphoric, and 50 c.c. of sulphuric acids (all concentrated), and the solution is evaporated to fumes; it is then cooled, diluted, oxidised with potassium permanganate, and cooled

again, 50 c.c. of hydrochloric acid (1 : 1) are added, and the solution is boiled down to copious fumes. The mass is dissolved in 250 c.c. of water, and the blue liquid, heated to 80° C., is titrated with permanganate solution; the iron equivalent of the latter being known, $V = 0.915 \text{ Fe}$.

Detection of Vanadium. A. Fölsner. (Chemiker-Zeitung, 1929, Vol. 53, p. 250). The hydrogen peroxide test was found to be unreliable for minute quantities, and the author uses lead acetate. For detecting vanadium in steel, he evaporates the *aqua regia* solution to dryness, filters off the silica, and precipitates the iron with caustic soda; he acidifies the filtrate with acetic acid and adds a lead acetate solution. He states that a faint but distinct turbidity is obtained with a concentration of 0.03 grm. of vanadium per litre.

Separation of Molybdenum and Vanadium in Steel. J. Kassler. (Zeitschrift für analytische Chemie, 1928, Vol. 74, pp. 276–286). The vanadium is precipitated by caustic soda in an acid solution (HCl or H_2SO_4) in the presence of a ferrous salt. The precipitate contains all the iron and vanadium, while the molybdenum remains in solution.

The Determination of Aluminium in Steel. A. T. Etheridge. (Analyst, 1929, Vol. 54, Mar., pp. 141–144). The method described does not include any aluminium present in the steel as alumina inclusions, as it deals only with the acid soluble material. The steel is dissolved in hydrochloric acid; the solution is oxidised with the minimum amount of nitric acid, evaporated to a low bulk, transferred to a separating funnel, and the iron is extracted with ether. The liquid is treated with sulphuric acid and electrolysed over a mercury cathode. The electrolyte is evaporated, traces of mercury are removed by hydrogen sulphide, the filtrate is boiled down, and the alumina precipitated with ammonia, methyl red being used as an indicator. This precipitate contains phosphorus pentoxide, ferric oxide, manganese oxide, and possibly chromic oxide; corrections are then applied by fusing it with 1 grm. of potassium bisulphate (free from iron), and estimating the amounts of the various impurities present by methods described in the paper. Finally, the result may be checked by a colorimetric test, using aurin-tricarboxylic acid. Full details of the process are given.

A Note on the Estimation of Tin in Steel and on Tinplate. Alice T. Godsell. (Swansea Technical College Metallurgical Society, Mar. 16, 1929). Whiteley's gravimetric method for the estimation of tin, although not rapid, gives concordant and accurate results. For the volumetric estimation of tin in mild steel and on tinplates by means of iodine the use of sulphuric rather than hydrochloric acid as solvent is strongly recommended for the following reasons: (a) Much better "end-point"; (b) fewer precautions in cooling necessary; (c) absence

of fumes; (d) much more reliable and concordant results. A suitable iodine solution for the determination of tin on tinplate is one containing 38.9 grm. of iodine per litre, 1 c.c. of which is equivalent to 1 oz. per standard box when determination is carried out on 2 sq. in. of tinned sheet.

The Determination of Silicon in Ferro-Silicon and Other Ferro-Alloys. A. Stadeler. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Jan., pp. 425-436). A critical examination of the methods usually followed for the estimation of silicon in ferro-silicon, ferro-chromium, ferro-molybdenum, ferro-vanadium, ferro-titanium, ferro-tungsten, ferro-phosphorus, silico-manganese, and silico-alumina.

Test for Copper in the Presence of Iron. L. Szebelledy. (*Zeitschrift für analytische Chemie*, 1928, Vol. 75, pp. 167-168). In the presence of ferric iron, copper (1 : 5000) may be tested for directly by means of potassium ferrocyanide if sufficient NH_4F , which prevents the formation of the blue precipitate, be added. The sensitiveness of the reagent for copper is increased by the addition of the NH_4F . The test is not applicable in the presence of ferrous iron.

A Method for the Estimation of Hydrogen in Steel. T. E. Rooney and G. Barr. (Paper read before the Iron and Steel Institute, May 1929: this *Journal*, p. 573).

Contribution on the Estimation of Oxygen in Steel by the Hot Extraction Process. G. Thanheiser and C. A. Müller. (*Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung*, 1929, Vol. 11, pp. 87-94). The authors describe their apparatus and experiments made to test the accuracy of the hot extraction method of estimating oxygen in steel; they conclude that even with the use of the high-frequency furnace the method has many sources of error. Chief of these is the fact that at 1500°C . only iron and manganese oxides are completely reduced; raising the temperature to reduce silica and alumina completely sets up trouble with the vacuum and also causes manganese metal to volatilise.

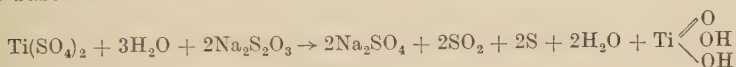
Improved Rapid Method for the Determination of Gases in Metals, Particularly Oxygen in Steel. W. Hessenbruch. (*Revue de Métallurgie, Mémoires*, 1929, Vol. 26, Feb., pp. 93-114). A translation into French of the original paper by Hessenbruch and Oberhoffer (*see Journ. I. and S.I.*, 1928, No. I. p. 938).

Methods of Determining the Oxygen Content of Iron and Steel. O. Meyer. (*Zeitschrift für angewandte Chemie*, 1928, Vol. 41, Dec. 1, pp. 1273-1276; Dec. 8, pp. 1295-1298). The author discusses the

residue and reduction methods, and reviews recent researches in Germany and elsewhere.

Method of Routine Analysis in Metallurgical Works. L. Persoz. (Revue de Chimie Industrielle, 1928, Vol. 37, Dec., pp. 382-384). A description is given of apparatus and its operation for the determination of oxygen in steel.

New Gravimetric Method for the Determination of the Titanic Acid Content of Iron Alloys. Separation of the Iron. J. Ciochina. (Zeitschrift für analytische Chemie, 1928, Vol. 73, pp. 40-46). The method is based on the reaction



The sample is dissolved in *aqua regia*, 5 to 20 c.c. of H_2SO_4 are added, the solution is heated until SO_3 fumes appear, a few drops of HF are added, the liquid is cooled and diluted with 50 to 100 c.c. of water, and neutralised with Na_2CO_3 ; 2 c.c. of H_2SO_4 (1 : 1) are added, followed by 6 gm. of $\text{Na}_2\text{S}_2\text{O}_3$. The solution is poured with constant stirring into 400 c.c. of boiling water, and the boiling is continued for 1 or 2 min. After cooling rapidly the liquid is poured through a filter provided with filter pulp (the first 50 c.c. are refiltered). The precipitate is washed with boiling water, ignited, and weighed as TiO_2 .

The Use of Liquid Amalgams in Volumetric Analysis. Part XI.—Determination of Phosphoric Acid by Using Zinc or Cadmium Amalgam. A. Someya. (Science Reports of the Tôhoku Imperial University, Sendai, 1928, Vol. 17, pp. 1289-1298). In this paper it is shown that under suitable conditions zinc or cadmium amalgam reduces molybdic acid completely to the trivalent condition. Based on this fact, a new and accurate method for the determination of phosphoric acid was worked out, which was shown also to give a good result in the determination of phosphorus in iron and steel.

ANALYSIS OF ORES AND FLUXES.

Analysis of Chrome Ores. T. R. Cunningham and T. R. McNeill. (Industrial and Engineering Chemistry, Analytical Edition, 1929, Vol. 1, Apr. 15, pp. 70-72). Methods for the determination of chromium, iron, silica, alumina, lime, and magnesia are described. Perchloric and sulphuric acids are used to decompose the sample. Alumina is separated from iron by means of cupferron, and is determined by precipitation with ammonia after oxidation of chromium to the hexavalent state by potassium chlorate.

Influence of Shaking on Various Precipitation Reactions. G. Thanheiser and P. Dickens. (*Archiv für das Eisenhüttenwesen*, 1929, Vol. 2, Mar., pp. 575-581). In following the usual analytical methods for chemically pure salts, the influence of shaking on the precipitation of barium, sulphur, calcium, and magnesium was investigated. A small shaking or jiggling apparatus holding several containers and driven by an electric motor is illustrated. It was found that after a shaking of 10 min. duration the precipitation of the above elements is quantitative, and the deposits are obtained in a form suitable for filtering. In phosphorus determinations the effect of shaking could not be estimated.

The Analysis of Fluorspar. G. E. F. Lundell and J. I. Hoffman. (*Bureau of Standards Journal of Research*, 1929, Vol. 2, Apr., pp. 671-683). In connection with the standardisation of the Bureau of Standards standard sample of fluorspar, old methods of analysis were tested and modified, and new methods were developed. The present paper sets forth the procedures that have been found desirable for the determination of carbonates, silica, calcium fluoride, sulphur, barium, lead, and zinc.

ANALYSIS OF FUEL.

The Analysis of Fuels by Means of the Bomb and the Orsat Apparatus ; How Mixtures of CO_2 and O_2 Behave. F. Bosnjakovic. (*Archiv für Wärmewirtschaft*, 1928, Vol. 9, Oct., pp. 309-318).

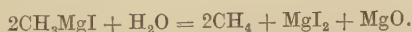
Exact and Rapid Method for Estimating the Total Sulphur in Coal. O. Hackl. (*Chemiker-Zeitung*, 1928, Vol. 52, Dec. 1, pp. 933-934). One grm. of the dried and powdered coal is mixed thoroughly in an iron crucible with 8 grm. of a mixture of equal quantities of KMnO_4 and Na_2CO_3 , the whole being covered with a layer of the mixture. A lid is put on the crucible and very gentle heat is applied at first ; later the temperature is raised, and finally the crucible is kept red hot for half an hour. After cooling, the mass is leached with 150 c.c. of boiling water ; a few drops of alcohol are added if the solution is coloured. The insoluble matter is filtered off and washed free from sulphate with slightly alkaline cold water. Hydrochloric acid is added, and the sulphate estimated as BaSO_4 in the usual way.

Estimation of Carbon and of Hydrogen in Fuels. L. Dauvilliers and Gost. (Paper read before the Second Congress on Industrial Heating, Paris, June 23, 1928 : *Chaleur et Industrie*, 1928, Vol. 9, Oct., pp. 68-72).

A Rapid Method for the Determination of Nitrogen in Coal. J. W. Whitaker. (Fuel in Science and Practice, 1929, Vol. 8, Mar., p. 145). The standard Kjeldahl method for the estimation of nitrogen in coal is tedious and somewhat liable to error because of (1) unsatisfactory conversion of the nitrogen to ammonia, and (2) unreliability in the end-point of the final back titration. A modification is described in which the coal is rapidly oxidised with strong sulphuric acid and potassium permanganate, and which is recommended as being more expeditious and accurate.

The Formation and the Determination of Oxides of Nitrogen in the Analysis of Gases. E. Richards. (Feuerungstechnik, 1928, Vol. 16, Jan. 15, pp. 17-18). The author puts forward evidence to show that at the high temperatures prevailing during the analysis of a gas by the explosion method an important amount of nitrous oxide may be formed. For its estimation the nitrous oxide is converted into nitric acid, and the latter is determined colorimetrically.

The Determination of Water in Fuels by Means of Methyl Magnesium Iodide. A. Taubmann. (Zeitschrift für analytische Chemie, 1928, Vol. 74, pp. 161-167). The author has investigated Zirewitinoff's method. The substance to be examined is treated with pyridine, which dissolves out the water; the solution is then agitated with methyl magnesium iodide, and two molecules of methane are evolved for each molecule of water, thus:



The method gives results agreeing with those obtained by desiccation over sulphuric acid *in vacuo*, and is more rapid; the results are more accurate than those given by drying at a raised temperature. The various substances occurring in naphtha have no effect on the accuracy of the process.

Practical Methods for Analysis of Gas. G. Neumann and F. Sträuber. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Mar., pp. 557-574). The article is concerned with methods and illustrated descriptions of apparatus for carrying out exact analyses of gas. The Orsat apparatus and accessories in particular are described with notes regarding their use, and appliances for taking samples of gas.

Notes on the Estimation of Hydrogen and Methane by Means of the Orsat Apparatus. H. A. Bahr. (Archiv für das Eisenhüttenwesen, 1929, Vol. 2, Feb., pp. 495-499). The old type of Orsat apparatus with hot-wire pipettes gives inaccurate analytical results. Two modified forms of the apparatus are illustrated and described, in which the sources of error in the older type are eliminated.

ANALYSIS OF REFRACTORY MATERIALS.

The Chemical Examination of Refractory Materials.—Part II. H. J. Van Royen. (Archiv für das Eisenhüttenwesen, 1928, Vol. 2, Dec., pp. 371–373). Methods are described for the chemical analysis of dolomite, magnesite, sinter dolomite, sinter magnesite, and magnesite bricks. These methods include the estimation of silica, iron, alumina, lime, magnesia, and manganese. The results of the analysis of the materials are recorded in tables.

NOTICES OF RECENT BOOKS PRESENTED TO THE LIBRARY.

“*Chemical Engineering and Chemical Catalogue.*” Fifth edition. A Catalogue of Heavy and Fine Chemicals, Raw Material, Machinery, Plant, and Equipment applicable to Production Industries, standardised, condensed, and cross-indexed. Compiled with the co-operation of leading British manufacturers. Editor, D. M. Newitt. 4to, pp. 401. London: Leonard Hill, Ltd. (Price 15s.)

The fifth enlarged edition of the “Chemical Engineering and Chemical Catalogue” continues to show an improvement upon the preceding editions. The firms co-operating in the production of the work have provided fuller and more comprehensive details of their products and manufactures, and it is designed to form a standard text-book of reference for consulting and contracting engineers, works managers, and others whose business it is to specify and purchase plant and equipment as well as material utilised in the manufacture of products for consumption. A useful feature is the section containing data concerning the materials of construction and apparatus used in the chemical and kindred industries.

CLEMENTS, F. “*Blast-Furnace Practice.*” Vol. I.—“*General Principles, Source, Preparation, and Handling of Raw Materials.*” 4to, pp. xxvii + 29–538. Illustrated. London, 1929: Ernest Benn, Ltd. (Price £3 3s.)

This volume is the first of a series which when complete will undoubtedly form the most important standard work on blast-furnace practice published within the last 50 years. It is written from the standpoint of the blast-furnace engineer and designer, the furnace operator, and the student who may desire to specialise in the construction of furnaces and auxiliary equipment and in the smelting of iron ores, in which spheres new problems constantly arise, the solution of which requires a vast amount of patient research, generally on an industrial scale. The book is divided into sections, which are so arranged that a natural sequence of subjects is followed. In order to ensure that the information should cover the latest practice and should embody every kind of method followed by the principal iron makers in different parts of the world, representative firms in nearly all countries where the smelting of iron on a large scale is successfully carried on have furnished particulars of the conditions under which they operate. Thus, apart from the help contributed by numerous British firms, information has been gathered from Canada, the United States, France, Belgium, Sweden, Germany, Czecho-Slovakia, Austria, Rumania, India, Australia, and Japan. The scope of the book is therefore world-wide, and the survey obtained gives a clear and proper conception of the stage of development at which the industry now stands. The present volume gives first an historical account of the development of the blast-furnace, and the following chapters then deal seriatim with: The Metallurgical Properties of Pig Iron; The Blast-Furnace and its Functions; Chemical Principles; Thermal Principles; Physical Principles; Geological Character and Geographical Distribution of Available Iron Ore Deposits; Economic Consideration of Available Iron

Ore Deposits; The Mining of Iron Ores; Preparation of Ores for Smelting; Fluxes and Iron-Bearing Auxiliaries to the Burden; Production of Blast-Furnace Coke; Air-Blast and its Functions; Handling of Materials. Readers will eagerly look forward to the appearance of the succeeding volumes.

"*The Engineer's Year-Book of Formulæ, Rules, Tables, Data, and Memoranda for 1929.*" A Compendium of the Modern Practice of Civil, Mechanical, Electrical, Marine, Gas, Aero, Mine, and Metallurgical Engineering. Compiled and edited by H. R. Kempe and W. Hanneford Smith. 8vo, pp. lxxvii + 3289. London, 1929: Crosby Lockwood & Son. (Price 30s.)

This valuable work of reference, which is now in its thirty-sixth year of publication, has again appeared in a revised and somewhat enlarged form. Fresh data and tables have been incorporated, and existing matter has been rearranged where considered necessary. The British Engineering Standards Association has authorised the inclusion in the volume of abridgments of their specifications, and abstracts of a large number of their Reports have been incorporated. Section XL is devoted to Metallurgy, and is divided into Part I., Metallurgy, and Part II., Welding and Cutting. Many of the data appear to have been taken from the publications of the Iron and Steel Institute, but the omission of information of certain recent important developments is still noticeable. Some revision of the section on Metallurgy would appear to be desirable to bring it into line with those dealing with civil, mechanical, electrical, and mining engineering.

LISTER, W. "*Practical Steelmaking.*" 8vo, pp. xii + 413. Illustrated. London, 1929: Chapman and Hall, Ltd. (Price 25s.)

The reason which prompted the author to produce this useful book was the lack of literature of a kind that appeals directly to the man actually engaged in working the steel furnaces, keeping them in repair, and casting the steel into the moulds. The several processes by which steel is produced on a large scale are described in simple language, beginning with the Bessemer process, acid and basic. Concerning these the author quite frankly states his opinion that, in the light of present-day requirements, they are both out of date and should now be relegated to their proper place in history. The acid and basic open-hearth processes are very fully treated, an extremely useful feature of these chapters being descriptions of methods for carrying out all sorts of repairs, large and small, and for dealing with emergencies and critical occurrences in the course of operations. Modifications in working to meet various requirements are described, and the details of design and dimensions of open-hearth furnaces are given. Further chapters discuss gas-producer practice, electric steel-making, pit-work, and the tapping and teeming of steel, with some notes on special alloy steels, heat treatment, and testing.

"*Mitteilungen aus dem Kaiser-Wilhelm-Institut für Eisenforschung zu Düsseldorf.*" Herausgegeben von Friedrich Körber. Band X. Abhandlung 96-115. La. 8vo, pp. 402. Illustrated. Düsseldorf, 1928: Verlag Stahleisen m.b.H. (Price 43.50 marks.)

This volume forms the tenth of the series containing the collected researches on iron, steel, slags, and ores, carried out in 1928 in the laboratories of the Kaiser-Wilhelm Institute for Iron Research at Düsseldorf. A considerable proportion of the investigations herein reported relate to the effects of deformation and cold-working on the mechanical properties of

metals produced by subjecting them to rolling and pressing operations or to tensile stress, and the results recorded add materially to the knowledge of this important subject. Abstracts of all the reports have already been published in Section II. of the volumes of the *Journals of the Iron and Steel Institute* issued in 1928, and the notes and references to be found there will serve as a guide to those who desire to consult the original articles. Reference to the earliest volumes of the *Mitteilungen* is now greatly facilitated by the inclusion in the present one of an Index covering the whole of the series of ten volumes published since 1920. It can only be said that the series forms an important work of reference which no metallurgical library can afford to be without.

PUPPE, J., and G. STAURER. "*Walzwerkswesen*" unter Mitarbeit von G. Asbeck, E. Buchmann, L. Carle, O. Emicke, H. Esser, H. Fey, O. Hengstenberg, C. Holzweiler, K. Hye v. Hyeburg, H. Illies, O. Johannsen, H. Jordan, C. Kiesselbach, M. Kophamel, F. Körber, F. W. Loh, K. Maleyka, M. Moser, A. Nöll, P. Oberhoffer, H. Ortmann, E. Peipers, A. Pomp, E. Popp, J. W. Reichert, E. Röber, K. Rummel, E. Schreiber, E. H. Schulz, E. Siebel, F. W. Siepke, W. Sonnabend, E. K. Weber. Herausgegeben von J. Puppe und G. Stauber. Erster Band. (Handbuch des Eisenhüttenwesens, herausgegeben im Auftrage des Vereins deutscher Eisenhüttenleute) La, 8vo, pp. xiii + 777, with 941 figures and 15 plates. Düsseldorf, 1929: Verlag Stahleisen m.b.H. Berlin: Verlag Julius Springer. (Price 85 marks, bound.)

This is the first volume of a work which, when the succeeding four volumes are published, is intended to form the most comprehensive treatise on rolling-mills for shaping all kinds of products manufactured from ductile iron and steel. The present volume, the first of the series, deals with the economics of the manufactured iron and steel industry, both from a national and world point of view, in great statistical detail. The imports, exports, and trading statistics for all countries of rolled products according to classes are set out, both in tabular and graphic form, as far as information on the subject is discoverable. The statistical returns range back to 1900. Information, both up to date and retrospective, is also given concerning tariffs and commercial treaties of the various industrial countries.

Then follows a highly interesting historical account of the development of the rolling-mill by that well-known authority, O. Johannsen. Records are wanting as to when and where rolls were first used for the purpose of shaping the metals, but there is extant a drawing by Leonardo da Vinci, dated about 1495, and reproduced in the book, showing a pair of rolls, worked by hand-gear, and with a metal sheet between them. Early in the seventeenth century, rolls were in regular use in several continental countries for the purpose of grooving lead strips for window frames. The first record of the application of power to driving rolls occurs in an old print published in Brunswick in 1763, according to which one, Johann Friedrich Müller, in 1683 laid before the ruling authorities of the Duchy of Brunswick the designs of a slitting mill for cutting iron sheets. This mill was driven by water-wheels and was in regular operation for a part of each year, the products being used for horseshoes, nails, and the like. The use of water-driven slitting mills extended considerably in the eighteenth century, and Rinman and Nordwall in Sweden designed a roll-turning lathe, by means of which rolling technique was much improved. Full reference is made to the British inventions at the end of the eighteenth century, relating to grooved rolls; then follow descriptions of the Belgian wire mill with Thomee's improvement by adding roughing rolls, Bedson's continuous wire mill, and,

finally, the writer brings the story down to the time of the development of the modern types of mills which are described, with a wealth of excellent illustrations. In all this work the greatest pains have been taken by the authors in the matter of historical accuracy.

There follows a chapter on the constitution and properties of wrought iron and ductile steel by the late Professor Oberhoffer and Dr. H. Esser, including a study of the constitution of carbon steels and the principal alloys of iron with other metals and metalloids, of inclusions, segregation, crystallisation, heat treatment, the cold-working effect, blue brittleness, &c. O. Hengstenberg furnishes a chapter on the constitution of non-ferrous metals and their alloys. M. Moser deals comprehensively with the testing of materials and machines for the performance of the numerous kinds of test to which materials of construction may require to be subjected. Further chapters follow on the cost of production in rolling-mills, the control of rolling-mill operations, the keeping of records, the theory of rolling and displacement of materials, and, finally, two long and important contributions by Emicke and Puppe on modern rolling-mill construction and design.

A valuable feature of the book consists in the large number of bibliographical references to authoritative sources, a list of which is given at the end of each section of the book. The manner in which the material is presented, the illustrations, and the general get-up, leave nothing to be desired.

REED, E. L. "*Photomicrographs of Iron and Steel.*" With a Foreword by A. Sauvour. 8vo, pp. xx + 253. Illustrated. New York, 1929: John Wiley & Sons, Inc. London: Chapman and Hall, Ltd. (Price 20s.)

The photomicrography of polished and etched specimens of metals has become indispensable as a means for securing records of microstructures for reference and future examination. The author of this book has conceived the happy idea of collating, preparing, and publishing a series of photomicrographs of irons and steels, including those of commercial quality and those which have been subjected to various standard mechanical and thermal treatments. The whole series, including those of alloy steels, numbers 193 micrographs altogether, and the utility of the book consists in the fact that these form what is practically a standard set of photomicrographs of a very wide range of materials in different conditions of treatment and composition, which the steel treater in the workshop or the student in the laboratory or works can apply as a basis for comparison. A second series follows the first, showing 25 photomicrographs of cast irons of various qualities, illustrating standard structures and compositions. Lists of the reagents used are given, with a statement indicating the composition of each, and the book concludes with an appendix, containing concise descriptions of the preparation of metallographic specimens, etching solutions for microscopic examination of steels and irons, microscopes and details of photomicrography, together with a statement of the standard definitions of terms relating to metallography and of tentative definitions of terms relating to heat treatment.

"*Taschenbuch für Berg- und Hüttenleute.*" Herausgegeben von F. Kögler. Zweite neubearbeitete Auflage. 8vo, pp. xvi + 1207, with 630 illustrations in the text. Berlin, 1929: Verlag von Wilhelm Ernst & Sohn. (Price 36.50 marks.)

The first edition of this pocket-book appeared a few years ago, and the favourable reception with which it met has necessitated the issue of a new

revised edition, in the preparation of which occasion was taken to include a large amount of additional matter. The book is intended to form a work of reference containing in as condensed a form as possible all information of importance to mining engineers and metallurgists. The metallurgical portion, which forms the latter part of the work, deals with the metallurgy of non-ferrous metals, and consists of the following chapters: Blowpipe Analysis, by Kolbeck; The Assaying of Metals, by Krug; General Metallurgy as applied to the smelting of non-ferrous metals, by Hoffman. This chapter deals with the physical and chemical properties of the more important metals, additions, fluxes, fuels, the purchase of ores and their mechanical preparation, gas-producers, chimneys, blowers, types of furnaces, the condensation and treatment of fumes, and furnace products. The next chapter, by E. Schiffner, deals very instructively with the extraction and refining processes of the metals themselves, those specially considered being copper, lead, silver, gold, zinc, cadmium, nickel, cobalt, tin, arsenic, bismuth, quicksilver. Electro-metallurgy is reviewed by Peters, and Scheuer contributes a chapter on the metallurgy of light metal alloys, their production, treatment, and properties.

The first three chapters of the book discuss the character of inorganic and organic minerals, and the next twenty-nine chapters are devoted to the science and technology of mining and winning of ores. For mining engineers and metallurgists the book is a source of the most up-to-date information on mining and treatment of ores and the metals extracted therefrom.

SAUERWALD, F. "*Lehrbuch der Metallkunde.*" 8vo, pp. xvi + 462, with 399 figures in the text. Berlin, 1929: Julius Springer. (Price 29 marks.)

This book is a summary of the information that has been made available by recent research work concerning the properties and constitution of metals, ferrous and non-ferrous and their alloys, and the modifications which can be brought about at will in those properties by change of chemical composition and by thermal or mechanical treatments. The first part of the work summarises the present state of knowledge of the science of metallurgy generally, with a discussion of the elemental nature of simple metals, their crystalline structure and the application of X-rays to the study and understanding of that structure. The constitution of binary and ternary systems in metals are then considered, and the effect of thermal and mechanical treatment in rendering them suitable for the various conditions which they are called upon to meet in service. Part II. of the book deals specially with the metallurgy of iron and steel, the constitution of iron, the production of it in its different forms, the manufacture of steel, and the characteristics imparted by different modes of treatment, both thermal and mechanical, the constitution of the principal alloy steels and the theory of magnetism.

The metallurgy of the non-ferrous metals is then summarised and reviewed on similar lines. Throughout the book the original authorities for the statements presented are quoted, and full reference is made to all the sources whence the illustrations have been collected. The whole work forms a highly useful compendium in a form which may conveniently obviate the necessity for a research student to turn up an infinite number of sources of reference.

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